ELECTRIC TRAINS

[*Frontispiece.*

L.N.W.R. Three-Coach Electric Train.

ELECTRIC TRAINS

BY

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PREFACE

It may be fairly claimed that an addition to the number of existing books hardly needs an excuse when the subject is "Electric Trains" There are few industries in so rapid a state of development as electric traction, and few important subjects on which the number of books is so comparatively small.

Of the books on the subject written in English, some have been allowed to become quite out of date, while others embody a great mass of statistics and data and cover a very wide range.

Others again are very advanced and their treatment of the subject, while essential to the specialist, demands a familiarity with mathematics beyond the scope of the student or of the railway engineer, whose chief business, after all, is the running and maintenance of trains

There appears, therefore, to be a need for a small book, primarily addressed to the railway engineer, dealing with the fundamental principles of electric traction, with the apparatus and devices in use, and with some convenient methods of making calculations required in practical working. At the same time the mathematical portions have been written as simply as possible for the benefit of the student, and, where possible, methods worked out from first principles rather than from formulæ have been preferred.

The scope of the book is indicated by its title, and questions of generation, transmission and transformation of electric power have been entirely omitted. Contact systems have been included, as they are inseparable from the train elements.

The writer wishes to thank the following gentlemen and firms:—

The Railway Commissioners and Chief Mechanical Engineer, New South Wales Government Railways, for permission to publish this book; Lt-Col F. A. Cortez-Leigh, R E., T.D., Electrical Engineer of the London, Midland and Scottish Railway, for permission to use information and photographs obtained by the writer during his nine years' experience with that

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It remains to state that the old names of the English railways before the amalgamations have been employed throughout for the sake of clearness , and that the " ton " used is the British or so-called " long " ton of 2,240 lbs., not the American or " short " ton of 2,000 lbs., nor the metric ton of 2,205 lbs.

R. E. D.

SYDNEY, 1926.

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CHAPTER I

INTRODUCTORY

Advantages of Electrification. To meet the ever-growing competition of tramway and motor-bus traffic, it has become necessary for those railways which serve suburban districts to give a faster and more frequent service of trains than before.

This requirement is best met by running a number of comparatively short trains at frequent intervals, and increasing the length of trains by combining two or more short trains into one unit at such times as may be necessary to handle the "rush-hour" traffic in the morning and evening.

As will be explained later, this flexibility in the capacity of the trains is very readily obtained with electric working.

It seldom occurs in suburban services that the distance between stops exceeds one mile and in the majority of cases this varies from a half to one mile.

Under these conditions, in order to obtain a reasonably high schedule speed, rapid acceleration and a high rate of braking is of primary importance, and it is the possibility of obtaining much higher accelerations than can be obtained with steam locomotives that constitutes one of the greatest advantages of electrical operation.

With steam-hauled trains, the acceleration is seldom greater than one half a mile per hour per second, and is usually less than this, whereas with electrical operation there is no difficulty in obtaining 1 to 1·5 m p h. per second in regular service. Even higher rates are to be obtained without great technical difficulty, the ultimate limit being fixed by the slipping of the driving wheels

Now in the case of an electrically driven vehicle the tractive force exerted on the wheels is uniform. (This is not quite strictly true, since each notch on the controller produces a sudden jerk, and the torque then falls steadily until the next notch. The con-

B

troller will, however, be fully round in less than 20 seconds.) In the steam locomotive the tractive force is pulsating and varies from a minimum to a maximum according to the position of the crank-pins relative to their dead centre. As a result, slipping takes place much more readily with steam locomotives, and it has been found that the driving wheels begin to slip when the tractive effort is 14 to 16 per cent. of the weight on the driving wheels, whereas with electric trains a tractive effort of 25 per cent. of the adhesive weight can be obtained without slipping Furthermore, the weight of the equipment in electric trains is usually distributed over a greater number of wheels and over a greater length of track than is usual with steam locomotives, which is a further factor which assists in securing a high rate of acceleration Moreover, since the weight of motors and gears is considerably less than that of an equivalent locomotive and boiler, the weight per axle is also considerably less, which in conjunction with the uniform tractive effort produces less wear and tear on the track.

For suburban service electric trains are almost invariably worked on what is called the Multiple Unit system. The units may consist of motor cars entirely, or, as is more usual, of a motor car and one or more trailers. In either case the unit is controlled from either end and this enables trains of any desired length to be made up by simply coupling up two or more of these units. With this system the tractive effort per ton weight of train can be maintained uniform, so that whatever the length of train the same acceleration can be obtained and the same traffic schedule kept.

Owing to the trains being capable of operation from either end there is no "running round" of the locomotive required at terminal stations and this leads to a great increase in the capacity of terminal stations, which is a very important consideration. For example, in the case of the Lancashire and Yorkshire Railway it was found that after the electrification of their Liverpool–Southport line it was possible to handle the traffic on two platforms where previously with steam-hauled trains it had required four platforms, or in other words the platform capacity of the station was doubled. The capacity of platforms at Waterloo Station, London, has been more than doubled by electrification.

It should be mentioned when making such a comparison that the same immunity from "running round" has been obtained with steam service by using so-called "push and pull motor

sets," comprising two coaches and a steam locomotive with a driver's compartment in the front coach and mechanical operation of the throttle from the front These " motor sets " couple up to another pair of coaches for the rush hour traffic forming a 4-coach train with locomotive in the middle Naturally the acceleration is not so good with the four coaches as with two, and the device is hardly applicable to very heavy trains but is considerably used for local services

A further very important advantage which electric traction has over steam traction for suburban working is in economy of fuel The electric train only uses power when actually running, whereas the steam locomotive has to burn coal whether the engine is actually running or is standing by ; but a still greater economy results from the fact that a much cheaper quality of slack coal can be utilised at the power station than can be used on the locomotive, and with the large and efficient boilers and turbo-generating sets the cost of coal per horse-power hour is much less than that of the best modern steam locomotives. Again, the proportion of the total time during which an electric locomotive or motor coach can be maintained in actual service is very considerably greater than with the steam locomotive, as there is no need for the loss of time involved in cleaning tubes, coaling and watering the engines, adjusting of brasses and the like. The bulk of the wearing parts of an electric train can be rapidly renewed, or the whole apparatus changed ; even the changing of a motor which involves lifting the car and removing the bogie can be carried out and the car restored for service in a few hours. The steam locomotive suffers in efficiency in wintry weather, while the electric locomotive or coach retains and indeed increases its service capacity.

Generally speaking, experience has shown that half the number of electric locomotives or motor coaches is more than equivalent to a given number of steam locomotives for service capacity.

The smoke nuisance in large towns is a matter which is beginning to be considered as serious, and anything which can be done towards its reduction is of value. The proposal has often been made for this reason alone to operate all trains by electric locomotives to a distance of several miles out of large cities and replace them by steam locomotives at that point On certain railways, the existence of a long tunnel has restricted the traffic under steam operation, the size and frequency of the trains being limited by the accumulation of noxious gases.

In a number of cases electrification has been resorted to in order to remove this restriction. The Baltimore belt line tunnel of the Baltimore and Ohio Railway, electrified in 1895, is a pioneer instance, but the Detroit River tunnel electrification, the Hoosac and Cascade tunnel electrification, the Simplon tunnel electrification and many others have been carried out to avoid the special difficulties of tunnel working. A tunnel accident, attributed to an accumulation of gases, was the prime cause of all the New York City lines being electrified into the City, while the bad conditions of tunnel working in the London Metropolitan Railway ultimately compelled electrification.

From the point of view of health and the damage due to the corrosive effects of a smoke-laden atmosphere, the smoke nuisance is at last being considered as a problem well worth solving.

It is a mistake to view the matter of electrical operation of railways as a question merely of superseding the steam locomotive by the electric locomotive or coach. The whole existing system has grown up round the steam locomotive, and the present method of working the traffic is based on the characteristics, needs and limitations of the steam engine. Numberless small coaling and watering stations are provided which involve storage of coal, and cost of time and wages; and there is also a steady stream of coal waggons to supply these places and of empty waggons back, all of which would be greatly modified if electrification were general and a few large power stations were the only consumers of coal and supplies.

In general the great power available at any point of an electrically worked railway, and the long continuous duty of which electrical apparatus is capable, remove limitations under which steam operation suffers, and thereby give greater freedom to traffic managers in their work. At the same time if the maximum of economy is to be obtained, certain features of electrical operation should be recognised. Chief among these is perhaps the desirability of spreading the whole effective load as uniformly as possible both in time and space, making the variations of load between passenger and goods departments as far as possible complementary and thus keeping the load factor of power station and sub-stations as high as possible, with consequent minimising of capital and running costs.

Influence of the Acceleration Rate. The influence of the rate of acceleration on the schedule speed is shown in Fig. 1 for the simplest possible case. The length of run is taken as half a mile and a constant rate of acceleration is assumed from

the start right up to the point of application of the brakes (which of course is the quickest possible way to do the run). Two acceleration rates are considered, 0·5 m p h. per sec., which may be taken as corresponding to steam service, and 1 0 m p.h. per sec corresponding to electric service The braking in each case is taken as 1·5 m p h per sec. The problem is to find the time taken in each case and hence the average running speed, etc.

First draw the two speed-time curves A and B corresponding to 1·0 and 0·5 m p h. per sec. respectively. Remembering that

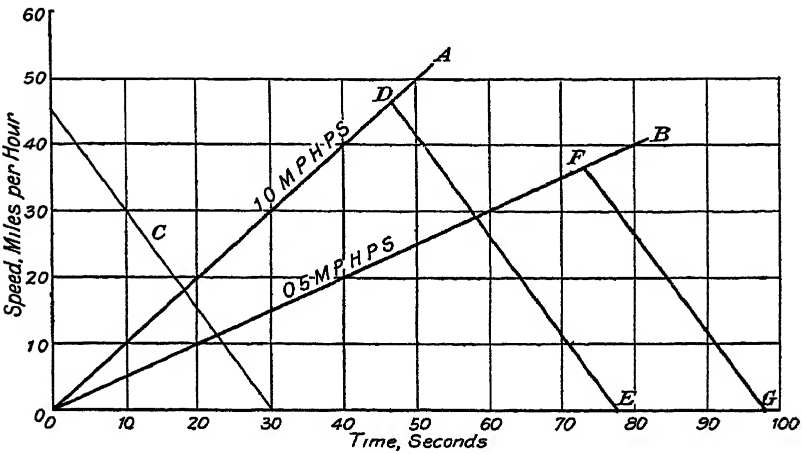


FIG 1.

$v = at$, i e speed = acceleration × time, we see that with constant acceleration the speed is directly proportional to time, so the speed-time curve will be a straight line Choose a suitable scale, e.g. 1 in = 10 m.p h and 1 in. = 20 secs. In case A the speed after 60 secs. will be 60 m.p h., and in case B it will be 30 m p.h. Draw the lines in from these points to the zero and produce them.

Next draw a line of the slope of the braking rate. As this is a negative acceleration of 1·5 m p h. per sec, in 30 secs. the speed will have fallen from 45 m.p h to zero The line C therefore shows the slope of the braking rate A line therefore has to be drawn parallel to the line C to cut the speed line OA at some place such as D, and OB at F The problem is to find these points. Now a little thought will make it clear that the

area of the speed-time curve must equal the distance covered, i e the area of the triangle ODE or OFG must be, to the correct scale, half a mile. Now to the scale chosen 1 sq in would mean 10 m.p.h continued for 20 secs., i.e.

$$\frac{10 \times 20}{3,600} \text{ miles} = 0{\cdot}0556 \text{ mile}$$

Hence the area of each triangle must be to our scale

$$\frac{0{\cdot}5}{{\cdot}0556} = 9 \text{ sq in.}$$

Either by using a planimeter or by the ordinary use of squared paper, it is a simple graphical exercise to place DE and FG so that the areas of the triangles ODE and OFG are each equal to 9 sq. in If this is done it will be found that E corresponds approximately to 77 secs, and G to 98 secs.*

$$\text{Now the average running speed} = \frac{\text{distance travelled}}{\text{running time}}$$

$$\text{and schedule speed} = \frac{\text{distance travelled}}{\text{running time} + \text{time of stops}}.$$

In our example,

$$\text{the running speed for Case A} = \frac{0{\cdot}5}{77} \times 3,600 = 23{\cdot}4 \text{ m p.h}$$

$$\text{the running speed for Case B} = \frac{0{\cdot}5}{98} \times 3,600 = 18{\cdot}4 \text{ m.p.h.}$$

If we allow for 20-second stops at stations, maximum schedule speed possible for Case A $= \dfrac{0{\cdot}5}{77 + 20} \times 3,600 = 18{\cdot}5$ m p.h.

maximum schedule speed possible for Case B

$$= \frac{0{\cdot}5}{98 + 20} \times 3,600 = 15{\cdot}2 \text{ m.p.h.}$$

* It is of course very simple to calculate these points instead of adopting graphical methods. In case A we have two triangles whose bases are $\frac{x}{2}$ and $\frac{x}{3}$ when x is the height.

$$\text{Then total base} = \frac{x}{2} + \frac{x}{3} = \frac{5x}{6} \text{ and area } \frac{5x^2}{12} = 9$$

whence $x = \sqrt{21\ 6} = 4{\cdot}65$, i.e. $46\frac{1}{2}$ m.p h.
and base $= 3{\cdot}88$, i.e 77·6 secs.

$$\text{In case B, total base } x + \frac{x}{3} = \frac{4x}{3} \text{ and area } \frac{2x^2}{3} = 9$$

whence $x = \sqrt{13{\cdot}5} = 3\ 67$, i.e. 36 7 m.p.h.
and base $= 4{\cdot}89$, *i.e.* 97·8 secs.

Thus the electric working shows a saving of 21 secs., or an increase of 21·7 per cent. on the schedule speed.

Now the above example shows a curve with a steady acceleration up to the point of application of the brakes. In practice, however, it is usual to cut off power when a certain speed is reached, and run as far as possible on the stored up kinetic energy before applying the brakes. Fig. 2 shows the type of curve obtaining in ordinary city service for runs of about half a mile. The speed curve to begin with is a straight line of constant acceleration up to the point *a* when the controller is right round and all resistance cut out, from *a* to *b* is the "free running" curve, whose shape depends on the motor characteristic; power is shut off at *b* and the train runs at a speed which

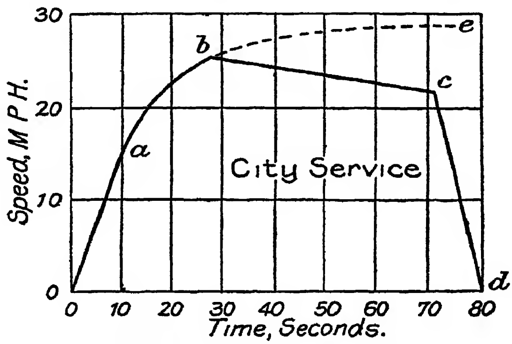


FIG 2.—Speed-Time Curve.

would be steady if there were no mechanical friction but actually falls slightly until brakes are applied at *c*, bringing train rapidly to rest at *d*. The period from *b* to *c* is called coasting, i.e. running on the stored kinetic energy, reduced only by mechanical friction. For ordinary continuous current railways using series motors, the accelerating current is maintained practically constant during the period of starting, i.e. until controller handle is right over. The rate of acceleration depends on the rate at which the rheostats are cut out and the average current allowed. When full voltage is applied to the motors, current and torque will decrease as speed increases. Hence the speed will gradually increase until the tractive effort just balances the frictional resistance to motion. The shape of this part of the curve depends primarily on the motor characteristic, but is affected by the mechanical friction, shape of ends of the train and wind resistance.

If power had not been cut off at *b*, the speed would have followed the dotted line, increasing slowly until train is running at a constant speed, at *e*.

From *o* to *a* is often called rheostatic acceleration (for D.C series motors) *a* to *b* is often called running on the speed-time curve, or " free running."

The student will have much to do with speed-time curves or " run curves," as they are often called, and it will be well to study the various forms obtaining for various services

Fig. 3 shows a curve corresponding to suburban running

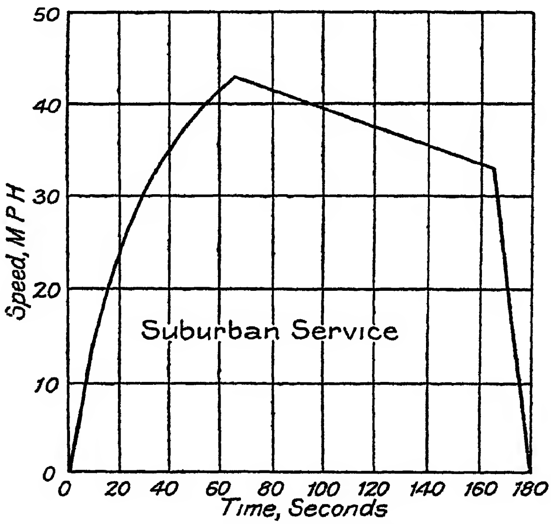


FIG. 3.—Speed-Time Curve.

distances of $1\frac{1}{2}$ to 2 miles over a stretch of 20 miles or so, and Fig 4 shows a typical main line run of several miles between stops. Illustrating a City service we see in Fig. 2 high acceleration and braking rates, and short free running, in order to secure as much coasting as possible, and thus to minimise power consumption. This type of curve gives a very rapid service but is expensive in power and needs a very frequent service of trains to pay its way. It is thus eminently adapted to " tube " service.

The suburban service (Fig. 3) needs a high acceleration and braking to attract passengers and thus to compete with buses

and trams. It allows longer free running and longer coasting periods

For main line or non-stop runs (Fig. 4) a long free running period may be obtained and probably a period of constant speed Naturally high acceleration and braking are here relatively unimportant.

The acceleration rate is taken to mean the rate taken over the period O*a* in Fig. 2, i e the straight line acceleration during "notching up" Its value varies between 1·0 and 1·5 m.p h per second, a figure round about 1·3 being the average for suburban electrifications of recent construction

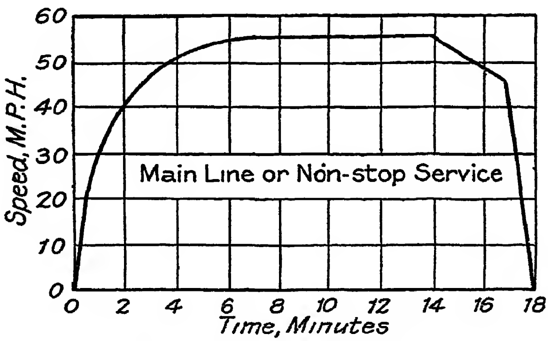


FIG 4.—Speed-Time Curve.

Effect of Acceleration Rate on Energy Consumption. A high acceleration necessitates a heavy starting current, but the motors are on the rheostats for a shorter time. For example, a tramcar took 101 amps. per motor to give 1 m.p h. per sec. The speed when in full parallel was 20 m.p.h. ; the time during which rheostats were in circuit was 20 secs. The same car took 135 amps. per motor to give 1·5 m p h. per sec. ; the speed in full parallel was 18·1 m.p h. and time on rheostats 12·1 secs.

The consumption for the run at 1·0 m.p.h. per sec acceleration was, therefore, $101 \times 20 = 2{,}020$ amp secs

The consumption for the run at 1·5 m.p.h. per sec acceleration was $135 \times 12{\cdot}1 = 1{,}630$ amp secs.

It will be seen, however, that the peak load is higher for the high acceleration.

The curve shown in Fig. 5 shows the large amount of energy saving achieved by the Manhattan (N.Y) Railway by increasing the acceleration over the whole of their system.

A high acceleration gives a high speed quickly and thus allows of a longer coasting period with consequent economy of either energy or time as preferred. A low accelerating rate means less coasting, and brakes have to be applied at a higher speed On the other hand, a high starting current increases the heating

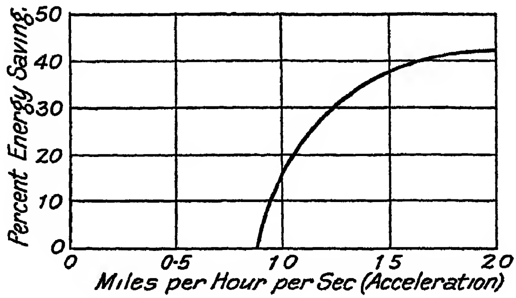


FIG. 5.

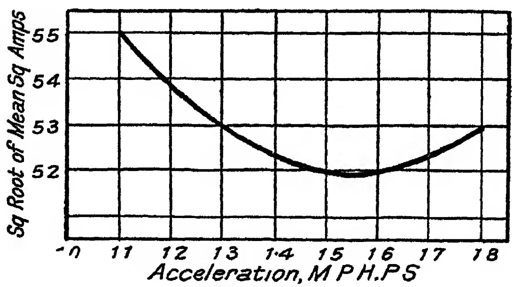


FIG. 6.

of the motors, but it is on for a less time. For a given run, the result of these opposing tendencies is that first one and then the other effect predominates and there will be one rate of acceleration at which the heating will be a minimum. This is shown graphically in Fig 6. (Heating being in proportion to the square of the current, the ordinates are taken as the square root of the mean square of the current.)

Limitations to Acceleration Rate.

(1) Weight of equipment. A very high acceleration involves large, heavy and expensive motors.

(2) High peak load. A high peak load on sub-stations and

power stations involves the installation of a relatively large amount of plant. Where there is a frequent service of short distance trains the peaks will overlap and smooth out the load curve, but where the service is infrequent the peak load becomes very important

(3) Discomfort to passengers If the number of controller points is sufficient and the rheostats accurately graduated, a high acceleration rate can be obtained without excessive jerk to passengers Otherwise starting is very jerky and disagreeable. There is naturally a limit to what is permissible in even the best cases

(4) Cost of equipment, control gear, and rolling stock, all of which must be stronger if a very high acceleration is used.

(5) High maintenance costs, due to heavy wear and tear

(6) Cost of energy Energy consumption may be low if stations are wide apart, but if close together and if a high acceleration is used in conjunction with a high braking rate to reduce running time, then energy consumption will be high.

In any given case the acceleration must be chosen by carefully balancing up all the factors concerned, and ultimately depends on the relation between the rate of interest on money and the probable revenue to be earned by the attractiveness of the service ; and on the distance between the stations. In a densely populated district, with short distances between stations, where the railway desires to electrify to meet keen competition from trams and motor omnibuses, a very high acceleration might be imperative and prove to be financially sound.

CHAPTER II

MECHANICS OF TRAIN MOVEMENT

Measurement of Speed. Speed is sometimes measured by a magneto dynamo driven from a train axle and connected to an indicating or recording voltmeter suitably calibrated to read the speed direct in miles per hour. A more reliable method is to use a good make of motor-car speedometer, belt-driven by a pulley from a train axle fitted to the bogie frame and connected by a flexible shaft through a hole in the floor of

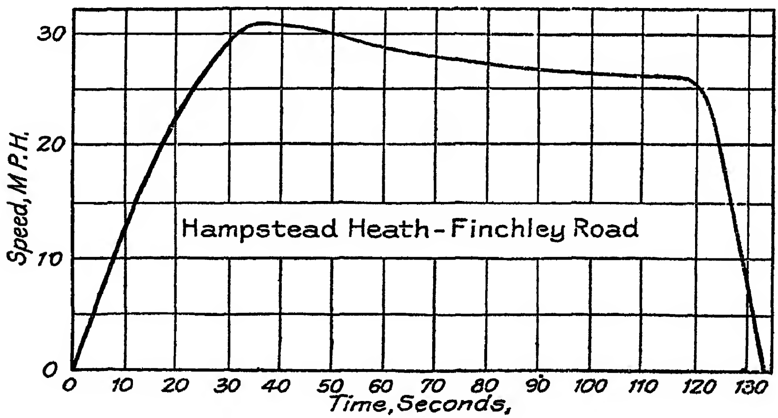


FIG. 7.

the coach to the instrument. There must be enough slack allowed to take up the radial movement of the bogie in rounding curves. The diameter of the pulley must be adjusted for the diameter of the tread of the wheel and for the axle diameter, and the train wheel must not be much worn if great accuracy is desired. For example, if the speedometer drive was calibrated for wheels of 42 in. diameter, and is used when the wheels are turned down to 39 in., the instrument will show readings which are 7 per cent. high. Whether a permanent

magnet dynamo or a speedometer is used the drive should be taken from a trailing axle, since a driving axle would register any slipping of the wheels and thus give an unreliable reading. A speed-time chart plotted from readings taken every 5 seconds using a Stewart Magnetic Speedometer is shown in Fig. 7. Some care must be taken to avoid bends in the flexible shaft, and to use some belt compound to prevent all slipping. This instrument has proved very satisfactory, though it required the belt to be taken off and crossed for the return journey. A speedometer working on the centrifugal principle removes this objection and indicates in either direction.

Measurement of Acceleration. The acceleration can readily be found from a speed-time curve made as described above, but the speed is changing so rapidly at the beginning that the first few readings may not be sufficiently accurate for the purpose of calculating acceleration during the first 15 seconds or so The deceleration, or braking, rate can, however, be found from this curve with sufficient accuracy.

The accurate measurement of the acceleration of a train is a somewhat difficult matter without special instruments. A method which has been used is to stand on the foot-board of the coach and throw down on to the track at intervals small paper bags filled with white chalk powder. The intervals may conveniently be of 5 seconds each, and one operator using a stop-watch can carry out the test. The distances between the centres of the white marks thus made can afterwards be measured, and from the distance travelled in each 5 seconds, the acceleration can be found either by calculation or by plotting the time—total distance curve. Another method is to place white stakes in the ground at the side of the track at equal distances of about 10 yards, and note the time of passing each stake This method involves specially preparing the track beforehand and running the train exactly up to the first stake before starting. Both methods have obvious disadvantages and both need very great care to give reliable results.

For accurate results some form of accelerometer must be used A very rough form of this instrument can be arranged as follows, and it has the merit of showing most clearly the inertia principle upon which all accelerometers are based A 2-ft. rule (Fig 8) is opened out and a weight suspended on a thread from a pin fixed $1\frac{5}{8}$ in from the top end. The hinge is then swung over until the thread hangs over the 3-inch mark. The length of thread from the pin to the 3-in. mark will be approxi-

mately 16·1 in. If the instrument is held in the direction of motion of the train, 1 ft. per second per second acceleration will cause the weight to lag behind and deflect the thread half an inch, i.e each half-inch division will correspond to 1 ft per sec. per sec. If the thread be attached at a point $6\frac{5}{8}$ in from the end instead of $1\frac{5}{8}$ inch, each half-inch deflection will correspond to 1 mile per hour per sec.

The mechanics of this arrangement are as follows. Referring to Fig 8, in which the arrangement is shown diagrammatically, if an acceleration of 1 ft. per sec. per sec. be imparted to the train, the weight will tend to lag behind owing to its

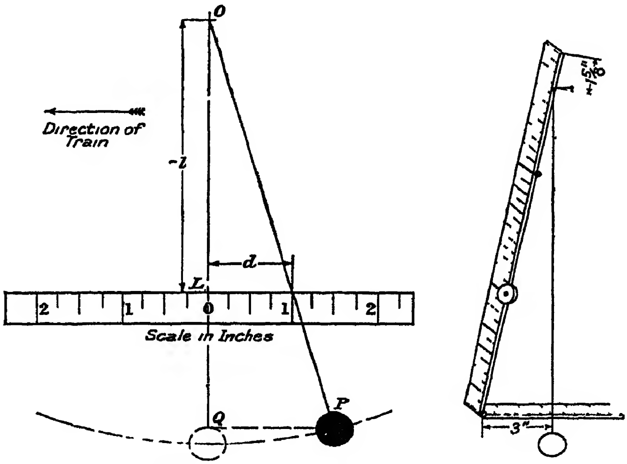


Fig 8—Simple Accelerometer.

inertia and will appear to swing backwards to the position OP shown on the diagram Let the weight be W lbs. Now the inertia force acting horizontally on the weight will be .—

$f = ma = W/32{\cdot}2$ lbs, i e. the horizontal force acting on the weight is 1/32 2 of its weight.

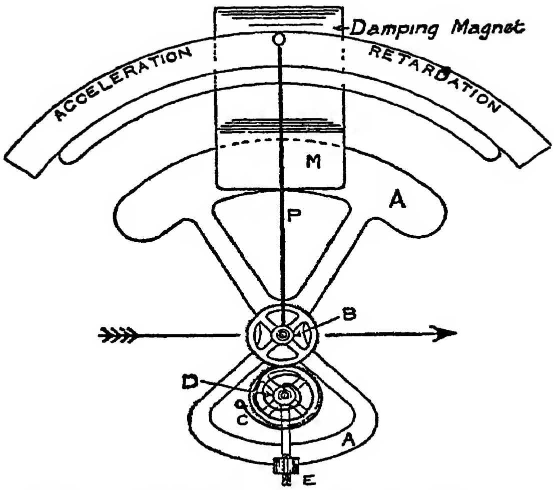
The diagram is its own triangle of forces, where

OP = the tension in the string, the resultant of OQ and QP.
OQ = the force due to gravity = W
QP = horizontal accelerating force = 1/32·2 of OQ

Hence for the length of string used the deflection QP is proportional to the acceleration of the train, to measure which directly it is only necessary to fix a scale at a convenient place.

For example, if an ordinary inch rule be fixed at L, where OL is made 32 2 in , then each inch deflection d, corresponds to 1 ft. per sec per sec. acceleration In the 2-ft rule instrument, by similar triangles, l is 16·1 and each half-inch corresponds to 1 ft per sec. per sec.

The weight and length of string may be of any dimensions, and it is easy to tilt the board or otherwise to damp the swinging when necessary The apparatus can be rigged up in a few minutes and the student who has not access to a first-class



[Fig. 9.—Diagram illustrating principle of Wimperis Accelerometer.

accelerometer can gain much information with it in tubes, suburban trains, etc., both as regards acceleration and retardation, which of course is measured on the reverse side of the scale.

The best instrument for accurate observation of acceleration is the Wimperis Accelerometer.* This consists essentially of an aluminium sector A (Fig. 9) fixed to a spindle B, which is mounted vertically in jewelled bearings The sector is mounted eccentrically, i.e. the centre of gravity does not coincide with the axis of rotation, and therefore an accelerating force applied to the whole in the direction of the arrow will produce a rotation of the spindle (and hence of the pointer attached to it) by reason

* Manufactured by Messrs. Elliot Bros., Lewisham.

of the greater inertia of the larger side of the sector. The rotation of the spindle B is restrained by the hair-spring C, fixed to another spindle D, which is geared by 1 : 1 gearing to the main spindle The spindle D also carries a compensating balance-weight E, which is adjusted to have a moment of inertia equal to the sector and pointer, the centre of gravity of the sector and compensating balance-weight being contained in a plane passing through D and B. In this manner the sector and compensating balance weight have equal and opposite moments about the spindle B in a direction at right angles to the motion. This is important, since it means that the instrument is only affected by accelerating forces which have a component along the direction of motion The instrument is therefore independent of rail curvature and super-elevation; moreover, if it is used on an inclined track, the acceleration shown represents the equivalent acceleration which the train would be doing on a level track, which is the figure the train engineer usually wants to ascertain. A damping magnet is fitted to control the deflection and the instrument reads acceleration in the forward direction in feet per sec. per sec. and retardation in the reverse direction, either in feet per sec. per sec. or in lbs. per ton.

The instrument is of very general utility, for it can be used to measure gradients directly, or if set in a plane so that the arrow is along the direction of motion it can be used by permanent-way engineers to measure super-elevation. It is far more useful still in its recording form, and gives a large-sized chart of the actual acceleration and retardation It is fitted with an auxiliary pen operated by a pneumatic bulb which can be used in conjunction with a stop watch to mark 5 seconds intervals, etc , or as shown in the reproduction of an actual chart (Fig 10) to mark the time of the various controller points. The instrument can be fixed to a small wooden stool, is very robust in use and does not need any shock-absorbing devices. From the chart obtained during the period of "notching up" it is a simple matter to find the area of the curve by means of the planimeter, and dividing this by the length of the base, a figure is obtained which gives the average acceleration during this period. Although the travel of the pointer is a radial one, the error caused by this method is insignificant if the average acceleration obtained is read off the radial scale. The accuracy is surprisingly good and is well maintained after continuous usage, and the writer has succeeded in integrating a complete chart from station to station by means of the planimeter and

thus obtaining a speed-time curve whose area gave the distance covered which latter agreed with the known distance within a few per cent.

Fig. 10 shows a reproduction of an actual acceleration chart as measured with this instrument. The distance between the horizontal ordinates is $1\frac{1}{4}$ secs, and the curved vertical ordinates are graduated in feet per sec. per sec. With the particular train control equipment, the *a* notch is a mere re-arrangement of contactors prior to the parallel "bridging" notch *b*, and the motor current falls exactly as if the controller had been kept

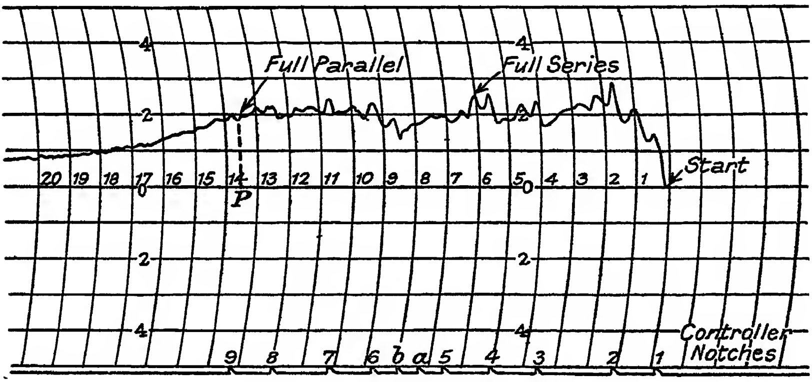


FIG 10—Accelerometer Chart

on the 5th or full series position Full acceleration rate is restored at the first parallel point "6" and the temporary loss of acceleration is clearly shown on the chart

To find the average acceleration over the "notching up" period from this chart, the procedure is as follows: Measure with a planimeter the area above the zero line from "start" through "full series" and parallel down the dotted line to P and back to "start." This area measures 1·95 sq. in. Length to P is 3·3 in Scale of ordinates 1 in. = 3·33 ft. per sec. per sec.

$$\text{Mean height} = \frac{\text{Area}}{\text{Length}} = \frac{1{\cdot}95}{3{\cdot}3} \text{ in.}$$

$$\text{Mean acceleration} = \frac{1{\cdot}95}{3{\cdot}3} \times \frac{3{\cdot}33 \times 60}{88} \text{ m.p.h. per sec.}$$

$$= 1{\cdot}34 \text{ m p h. per sec.}$$

The operation of calculating this figure from a given chart is a matter of a few minutes only.

As a matter of interest, the integration of this chart is shown worked out in the following table, and the results plotted in Fig. 11. The method is to take small time intervals, find the

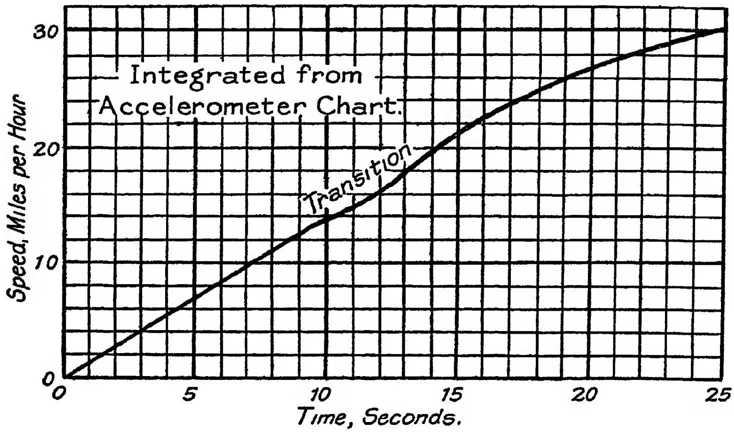


FIG. 11.

Point on Chart.	Time Interval Secs	Area Sq in.	Mean Acceleration M P H P S	Speed Increment M P H	Total Speed M P.H
1	1	·1	0 96	1 04	1·04
2	1¼	·16	1 45	1·81	2·85
3	1¼	·15	1 36	1 69	4 54
4	1¼	·16	1·45	1·81	6 35
5	1¼	·15	1 36	1·7	8·05
6	1¼	17	1·55	1·93	9·98
7	1¼	16	1·45	1·81	11·79
8	1¼	·14	1·27	1·59	13 38
9	1¼	·11	1·00	1·25	14 63
10	1¼	·17	1 55	1·93	16 56
11	1¼	·18	1 64	2 04	18·6
12	1¼	·18	1·64	2 04	20 64
13	1¼	·15	1 36	1·7	22 34
14	1¼	·14	1·27	1·59	23 93
15	1¼	·12	1 09	1·36	25·29
16	1¼	·12	1·09	1·36	26 65
17	1¼	·09	0 82	1 03	27·67
18	1¼	08	0 73	0 91	28·58
19	1¼	·08	0 73	0·91	29·49
20	1¼	·07	0·64	0·79	30·28

mean acceleration and hence the speed increase over such intervals. The curve is of interest in showing the falling off of speed during the transition period As mentioned previously this method can be used to complete a speed-time curve from station to station but the method is very laborious and a speedometer is greatly to be preferred.

Work done in Propelling a Train along Level Track. If the speed be constant, the only work done is that against frictional resistance.

EXAMPLE. Find the power required to drive a 100-ton train on level track at 30 m.p h. if the train resistance is 9 lbs. per ton.

$$\text{Power required} = \text{force} \times \text{speed}$$
$$= 100 \times 9 \times 30 \times \frac{5{,}280}{60} \text{ ft.-lbs. per min.}$$
$$= \frac{900 \times 30 \times 5{,}280}{60 \times 33{,}000} \text{ h.p.} = 72 \text{ h.p.}$$

Work done in Propelling a Train up Incline. Referring to Fig. 12, the force G acting on a weight W lbs. tending to pull it downhill is W sin α

Now gradients are usually expressed in the form of 1

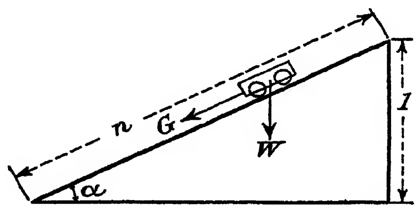


FIG. 12.

in n, i.e. in travelling along the gradient n ft. we have risen 1 ft.

Since $\sin\, \alpha = \frac{1}{n}$, the downhill pull on weight W is simply $\frac{W}{n}$ lbs. This gravity pull must be added to or subtracted from the other forces acting in calculating the power required.

EXAMPLE. The train in the last example is to travel up a bank of 1 in 40. Find the h p. required.

Downward force due to gravity

$$= \frac{W}{n} = \frac{100 \times 2{,}240}{40} = 5{,}600 \text{ lb.}$$

Train resistance $= 900$,,

Total force-resisting motion $= 6{,}500$,,

$$\text{Then power required} = \frac{6{,}500 \times 30 \times 5{,}280}{60 \times 33{,}000} = 520 \text{ h p.}$$

Note.—Gradients are sometimes, particularly in American practice, expressed in percentages. Thus a gradient of 4 per cent. is 4 in 100, or 1 in 25.

The maximum gradient encountered in practice never exceeds 1 in 20, while a gradient of 1 in 50 is considered steep.

Run Curves.

EXAMPLE. Plot a run curve from the following data :—

Constant acceleration of 1·1 m p h per sec. for 20 secs.
Coasting for 40 secs (neglecting friction).
Braking rate 2 m p.h. per sec.
Find total time requisite for the run, the distance covered, and the average running speed.

Speed after 20 secs. = 22 m p h.
Braking time, 22 m p h. to zero at 2 m.p.h. per sec.

$$\text{Retardation takes } \frac{22}{2} = 11 \text{ secs.}$$

$$\therefore \text{ total time} = 20 + 40 + 11 = 71 \text{ secs.}$$

Distance covered during acceleration

$$= \text{average speed} \times \text{time} = \frac{11 \times 20}{3{,}600} = 0{\cdot}0611 \text{ mile}$$

$$\text{Distance covered during coasting} = \frac{22 \times 40}{3{,}600} = 0{\cdot}2444 \text{ ,,}$$

$$\text{Distance covered during braking} = \frac{11 \times 11}{3{,}600} = 0{\cdot}0336 \text{ ,,}$$

$$\text{Total} = 0{\cdot}3391 \text{ ,,}$$

$$\text{Average running speed} = \frac{{\cdot}3391}{71} \times 3{,}600 = 17{\cdot}2 \text{ m.p.h.}$$

This curve is shown (full line) in Fig. 13.

Train Resistance. Train resistance is the sum total of all the frictional forces tending to retard the motion of a train.

It is made up of many different quantities and will be discussed in greater detail later on, in Chapter XI For the present it need only be stated that it is generally expressed in lbs per ton of dead weight of the train. Owing to train resistance the speed will fall during coasting To enable us to draw curves of the slope of the coasting speed, we must first convert

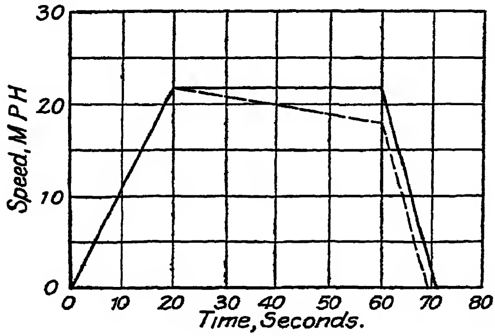


FIG. 13.

this quantity of lbs per ton into the equivalent (negative) acceleration.

The fundamental equation here applies, $f = ma$, i e. Force in lbs = mass (in lbs units) $\times$ acceleration (in feet per sec. per sec.)

To find the retardation corresponding to 10 lbs. per ton, therefore proceed as follows .—

$$a = \frac{f}{m} = \frac{10 \times 32{\cdot}2}{2{,}240} \text{ ft. per sec. per sec}$$

$$(f = 10 \text{ lbs.})$$

$$\left(m = \frac{1 \text{ ton or } 2{,}240 \text{ lbs}}{32{\cdot}2}\right)$$

$$= \frac{10 \times 32{\cdot}2 \times 60}{2240 \times 88} \text{ m.p h. per sec.}$$

$$= {\cdot}098 \text{ m p.h. per sec or nearly } {\cdot}1 \text{ m p.h per sec.}$$

It is worth memorising that 1 *lb. per ton is equivalent to* ·01 *m p.h. per sec.* Therefore 10 lbs. per ton resistance corresponds to a retardation of ·1 m.p h per sec., from which the coasting speed curve can be drawn, e g. over a period of 60 seconds the fall in speed will be $60 \times {\cdot}1 = 6$ m p.h.

EXAMPLE. Plot the curve for the same data as in the previous example, but assuming 10 lbs. per ton resistance during coasting.

As before, speed after 20 secs = 22 m.p h

10 lbs. per ton corresponds to ·098 m p h. per sec retardation, hence loss of speed in 40 secs = 40 × ·098 = 3 92 m p.h.

Therefore speed at point of application of brakes = 22 − 3·92 = 18 08 m.p h. (Average speed during coasting, 20 04 m p h)

$$\text{Therefore braking time} = \frac{18\ 08}{2} = 9 \text{ secs}$$

$$\text{Total time} = 20 + 40 + 9 = 69 \text{ secs.}$$

$$\text{Distance covered during acceleration} = \frac{11 \times 20}{3{,}600} = 0{\cdot}0612 \text{ mile}$$

$$\text{,,} \quad \text{,,} \quad \text{,,} \quad \text{coasting} = \frac{20{\cdot}04 \times 40}{3{,}600} = 0{\cdot}2227 \text{ ,,}$$

$$\text{,,} \quad \text{,,} \quad \text{,,} \quad \text{braking} = \frac{18{\cdot}08 \times 9}{2 \times 3{,}600} = 0{\cdot}0226 \text{ ,,}$$

$$\text{Total distance covered} = \underline{0{\cdot}3065} \text{ ,,}$$

$$\text{Average running speed} = \frac{{\cdot}3065}{69} \times 3{,}600 = 16 \text{ m.p h.}$$

The curve is shown dotted in Fig. 13

Applying what has been learnt to a more practical case, the following problem may be considered.

A train has a uniform acceleration of 1 25 m.p h per sec. for 18 secs Coasting time 38 secs. Train resistance 10 lbs. per ton. Braking rate 2·1 m.p h per sec. Draw the speed-time curve. Find the time taken, distance covered, average running speed and schedule speed, assuming 15 sec stops. Find the effect on the average running speed and time of run if the acceleration is increased to 1·4 m p.h. per sec.

Speed after 18 secs. = 18 × 1·25 = 22·5 m.p.h.
,, lost during coasting 38 × ·098 = 3·72 m.p.h.
,, at point of application of brakes = 18·78 m.p.h.
Average speed during coasting = 20·64 m.p.h.

Time to come to rest from 18·78 m p.h. at 2·1 m.p.h. per sec. retardation—

$$= \frac{18{\cdot}78}{2{\cdot}1} = 8{\cdot}94 \text{ secs.} = 9 \text{ secs. (approx.).}$$

Total time of run = 18 + 38 + 9 = 65 secs.

The curve can now be drawn in, Curve A, Fig. 14.

$$\text{Distance covered during acceleration} = \frac{22{\cdot}5 \times 18}{3{,}600 \times 2} = {\cdot}0562 \text{ mile.}$$

$$\text{,, ,, ,, coasting} = \frac{20{\cdot}64 \times 38}{3{,}600} = {\cdot}2179 \text{ ,,}$$

$$\text{,, ,, ,, braking} = \frac{18{\cdot}78 \times 9}{3{,}600 \times 2} = {\cdot}0235 \text{ ,,}$$

$$\text{Total distance covered} = {\cdot}2976 \text{ ,,}$$

$$\text{Average running speed} = \frac{{\cdot}2976 \times 3{,}600}{65} = 16{\cdot}5 \text{ m p h.}$$

$$\text{Schedule speed} = \frac{{\cdot}2976}{65 + 15} \times 3{,}600 = 13{\cdot}4 \text{ m.p h.}$$

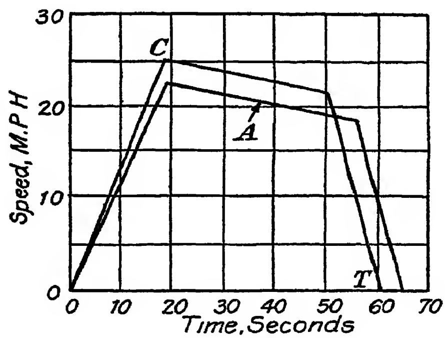


FIG. 14.

Suppose now the acceleration be increased to 1·4 m.p.h. per sec. for 18 secs. as before Find the effect on the average running speed and the time.

To do this, we must complete the speed-time curve, and this involves two unknown quantities. As the distance covered remains the same, the new curve must have an area equal to the original, but the braking and coasting positions will have changed That is, a new curve must be drawn having the same coasting and braking slopes as before. Now the position of the points C and T cannot readily be found by calculation, but is a simple matter with the planimeter, or can be done more laboriously, if a planimeter is not available, by the careful use of squared paper. In either case it is a matter of trial and error, and a few attempts will result in fixing T at about 61 secs.

The time saved by the increasing of acceleration is thus :—

$$4 \text{ secs. or } \frac{4}{65} = 6{\cdot}15 \text{ per cent}$$

$$\text{Average running speed} = \frac{{\cdot}2976}{61} \times 3{,}600 = 17\ 55 \text{ m.p h.}$$

which is an increase of 1·05 m p.h = 6·4 per cent.

INERTIA OF ROTATING PARTS

Force to Accelerate Train. The formula connecting force, mass and acceleration is the well-known :—

$$f = ma$$

when f is the force applied in lbs

m is the mass in lb -ft units $= \dfrac{\text{weight}}{32{\cdot}2}$

a is acceleration produced, in feet per sec. per sec

Since train weights are usually expressed in tons and train accelerations in miles per hour per second, the formula becomes for a train of weight W tons, and an acceleration A miles per hour per second .—

$$f \text{ lbs} = \frac{W \times 2{,}240}{32{\cdot}2} \times 1{\cdot}47\ A$$
$$= 102\ WA.$$

i.e. the force in lbs required to impart an acceleration of A miles per hour per second to a train weighing W tons is 102 WA. This is a useful formula to memorise

Inertia of Rotating Parts. In calculation work so far we have considered a train to be a dead weight and have used a simple mechanical formula to calculate the acceleration resulting from the application of a driving force to this dead weight. But in actual fact a train is not a dead weight. It contains armatures, gear-wheels, pinions, wheels and axles, all of which revolve and which require an additional driving force to accelerate them in a circular direction. Conversely, too, when a train is to be brought to rest the total energy stored up in it is not merely that of the dead weight moving at a certain speed in a straight line but also the "fly-wheel" effect of the revolving parts The effect of these revolving parts is therefore that the train behaves as if its weight were somewhat greater than the dead weight, and for calculation purposes the "rotary inertia" of the revolving parts is calculated and added to the dead weight. The resulting figure is termed the "net effective weight," and

is used instead of the dead weight for all calculations which involve tractive force and resulting acceleration

The usual formula for straight line motion, $f = ma$ becomes, for rotary motion (e g. a wheel), $fr = IA$

that is : torque = moment of inertia × angular acceleration

where f = force in pounds exerted at the periphery.

r = radius of wheel, in feet.

I = moment of inertia about its own axis, in lbs.-feet units.

A = angular acceleration in radians per sec per sec.

But if a = linear acceleration of a point on the periphery of the wheel, at radius r,

then $A = \frac{a}{r}$.

Also, the moment of inertia $I = mk^2$, where k = radius of gyration in feet

Substituting these values for A and I, we have :—

$$f = \frac{IA}{r} = \frac{mk^2a}{r^2} = m\left(\frac{k}{r}\right)^2 a.$$

Thus, instead of m in the original formula $f = ma$, we now have $m\left(\frac{k}{r}\right)^2$

Applying this to a train wheel, the force f is the force which is necessary to overcome the inertia of the revolving wheel, and to produce an angular acceleration such that the linear acceleration of a point on the tread of the wheel is a ft per sec. per sec This is additional to the force required to give the dead weight of the wheel a linear acceleration. The expression $m\left(\frac{k}{r}\right)^2$ is called the "rotary inertia mass," and $w\left(\frac{k}{r}\right)^2$ the "rotary inertia weight," where w is the dead weight.

Example. A wheel weighs 1,400 lbs. Diameter at tread is 40 in.

Radius of gyration is 15·4 in. Find the net effective weight of a pair of such wheels.

Rotary inertia weight is $w\left(\frac{k}{r}\right)^2$	$= 2 \times 1{,}400 \times \left(\frac{15 \cdot 4}{20}\right)^2$.
	= 1,660 lbs.
Dead weight, 2 × 1,400	= 2,800 ,,
Net effective weight	= 4,460 ,,

The same method can be applied to find the net effective weight of the gear wheels. For armatures a modification is needed on account of the gearing. Armatures on suburban electric trains usually drive the wheels through single reduction spur gearing.

$$\text{Thus gear ratio, } \gamma = \frac{\text{number of teeth on gear wheel}}{\text{number of teeth on pinion}}.$$

The angular acceleration of the armature is therefore $\gamma \times$ angular acceleration of wheel, i.e. $\frac{a\gamma}{r}$.

Hence the formula will be modified in the case of armatures, thus —

$$\text{Rotary inertia weight} = w\left(\frac{k\gamma}{r}\right)^2.$$

Where w = dead weight of the armature.
k = radius of gyration of the armature.
r = radius of driving wheel.

Example. An armature weighs 1,850 lbs. Find the net effective weight of 8 such armatures, if the radius of gyration is 7 in., and the diameter of the driving wheels is 43½ in. Gear ratio = 1 to 4·24.

$$\text{Rotary inertia weight} = w\left(\frac{k\gamma}{r}\right)^2 = 8 \times 1{,}850 \times \left(\frac{7 \times 4{\cdot}24}{21{\cdot}75}\right)^2 \text{ lbs.}$$

	= 12·3 tons
Dead weight, 8 × 1,850 lbs.	= 6·61 ,,
Net effective weight	= 18·91 ,,

Radii of Gyration.

For a solid cylinder	= 0·707 × outside radius.
For a steel tyred wheel	= 0·77 × radius of tread.
For a gear wheel	= 0·8 × radius of pitch circle.
For a D.C. or A.C armature	= 0·7 × external radius of core

The above constants for wheels and armatures are approximate only, as they depend on the particular design, but they are sufficiently accurate for most calculations.*

We are now in a position to work out the net effective weight of a complete train.

Example A three-coach L.N.W.R. train, made up of a motor-coach and two trailers, weighs 112 tons empty. The

* F. W. Carter, *I.E.E. Journal* (1913), Vol. 50, p. 436.

motor coach contains 4 motors, whose armatures weigh $18\frac{1}{2}$ cwt each Outside diameter of armature is $18\frac{7}{8}$ in. There are two four-wheeled bogies to each coach, and the weight of a wheel is 1,531 lbs. Diameter at the tread of the wheels is $43\frac{5}{8}$ in. Gear wheels weigh 581 lbs. each. Diameter of pitch circle = 30·7 in. Gear ratio = 1 to 3·33. Find the net effective weight of the train

Wheels. Total number—24.

$$\text{Rotary inertia weight} = 24 \times \frac{1{,}531}{2{,}240} \times \cdot 77^2 = 9{\cdot}73 \text{ tons.}$$

Armatures. Total number—4

Rotary inertia weight

$$= 4 \times \frac{18{\cdot}5}{20} \times \left(\frac{\cdot 7 \times 18{\cdot}875 \times 3{\cdot}33}{43{\cdot}625}\right)^2 = 3{\cdot}76 \quad ,,$$

Gear Wheels. Total number—4.

Rotary inertia weight

$$= 4 \times \frac{581}{2{,}240} \times \left(\frac{\cdot 8 \times 30{\cdot}7}{43{\cdot}625}\right)^2 = 0{\cdot}32 \quad ,,$$

Total rotary inertia weight	13·81	,,
Total dead weight	= 112·0	,,
Net effective weight	= 125·81	,,

The increase for the inertia effect of the rotating parts is therefore

$$\frac{13{\cdot}81}{112} \times 100 = 12{\cdot}3 \text{ per cent.}$$

This quantity varies from about 8 per cent to 13 per cent, and a figure of about 10 per cent. is usually taken as a good average for a complete multiple unit train, though for modern practice 12 per cent. is a better figure. It will be noticed from the above example that the effect of the gear wheels is practically negligible, and a very small error will result from neglecting them, or an allowance of about 3 per cent. to the additional effective weight can be made

Mr Carter gives the following useful approximations of the additional weight due to revolving masses :—

Armatures . .	2,800 lbs	each.
Gears . .	250 ,,	,,
Wheels . .	600 ,,	,,

These refer to average conditions for multiple unit trains.

The net effective weight obtained as above is needed if we

wish to calculate the acceleration produced by any given tractive effort.

EXAMPLE A tractive force of 3,840 lbs per motor is applied to the above train. What acceleration will be produced?

Total tractive force $= 4 \times 3{,}840 = 15{,}360$ lbs

$$a = \frac{f}{m} = \frac{15{,}360 \times 32 \cdot 2}{125 \cdot 81 \times 2{,}240}$$

$$= 1 \cdot 76 \text{ ft. per sec. per sec.}$$

$$= 1 \cdot 76 \times \frac{60}{88} \text{ m p.h. per sec.}$$

$$= 1 \cdot 2 \text{ m p.h. per sec.}$$

The calculation of a speed-time curve for a train from a knowledge of the tractive effort of the motors and its variations with variations of current, is performed by taking a number of small intervals and working out the acceleration and therefore speed. An example is worked out in the next chapter.

An interesting application of the same principle may be quoted. The L.N.W.R. train weighing 112 tons empty, was specified to have an acceleration of 1·2 m.p h. per sec. when loaded with 12 tons of passengers (allowing 16 passengers per ton)

To avoid loading the train for test purposes it was desired to calculate the corresponding acceleration when running empty.

Effective weight was taken as 12 per cent. above the dead weight Train resistance was assumed to be 8 lbs per ton.

Total effective weight empty = 125·5 tons.
Total effective weight loaded = 137·5 ,,

The acceleration will vary inversely as the effective weight if the difference in friction is neglected, i.e.

$$a = \frac{137 \cdot 5}{125 \cdot 5} \times 1 \cdot 2$$

$$= 1 \cdot 315 \text{ m.p.h. per sec.}$$

Train resistance due to weight of passengers only is 12×8 lbs. = 96 lbs.

Expressing this in lbs. per ton of empty dead weight $\frac{96}{112}$ = ·856 lbs. per ton.

In the case of an empty train the force which was absorbed in overcoming the extra friction due to passengers is now available for producing extra acceleration.

Acceleration produced by ·856 lbs. per ton = ·00856 m p h. per sec , which must be added to the previous acceleration figure to give the correction for the difference in friction due to the weight of passengers. The net equivalent acceleration of an empty train will therefore be .—

$$1{\cdot}315 + {\cdot}009 = 1{\cdot}324 \text{ m.p.h. per sec.}$$

Another practical application of this principle would be the addition of an extra trailer to a train when it may be desired to calculate the acceleration and motor loading resulting.

CHAPTER III

SERIES-PARALLEL CONTROL: BUILDING UP THE SPEED-TIME CURVE

SERIES-PARALLEL CONTROL

Traction motors require to exert their greatest tractive effort at starting, in order to accelerate the train; and the tractive effort during the accelerating period is usually about that corresponding to the full rated current of the motors.

Most electric motor coaches are fitted with either two or, more often, four motors, and if these were connected permanently in parallel and started up by cutting out sections of a rheostat, there would be a great loss of power in the rheostat, and it becomes necessary to use a more economical method of control.

Now the torque of a direct current motor is proportional to magnetic flux × armature current. In the case of a series motor supplied with constant current the torque and flux will remain constant. Hence, as in the case of a separately excited motor, an increase of voltage to the motor will cause a speed increase until the back E.M.F. rises to the new voltage across the terminals. The speed of a series motor is therefore proportional to the voltage applied to it.

Hence two similar series motors can be arranged in series for the first half of the starting period and in parallel for the second half, and if the current per motor is maintained constant throughout the operation the energy output will be the same as for plain rheostatic starting, but the energy wasted will be much less. The method consists in principle in starting up a motor by using the back E.M.F. of a similar motor in series with the first, to oppose that part of the applied voltage which would otherwise have to be absorbed in rheostats. It is invariably employed on D.C. railways, and in addition to the economy of energy it gives two economical running speeds. If the train is kept running for a long time with some resistance in circuit the rheostats will

become overheated as they are not designed for continuous service and there will be a wastage of energy. In full series and in full parallel no resistance is in circuit, and the series parallel method therefore gives us the two advantages of economy of energy, and two economical running speeds, approximately half and full speed respectively. If a driver sees that the next signal is against him as he starts from a station he will usually bring his controller to full series and keep it there until he is allowed to proceed to full parallel, thus reducing the probability of having to pull up and start again.

We shall now consider the matter quantitatively to find how to calculate the rheostatic losses in each case

Plain Rheostatic Starting. Consider first two motors to be started up in parallel by the plain rheostatic method, as shown diagramatically in Fig 15, in which A, F and R represent

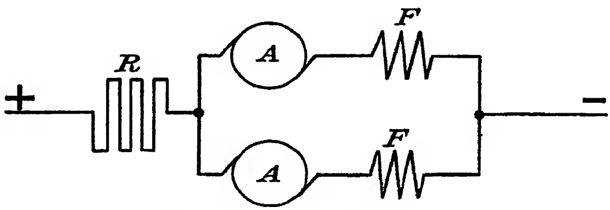


Fig. 15—Plain Rheostat Starting Connections.

armature, field and rheostats respectively. On switching on current, before the armature has had time to revolve we shall have a voltage drop across each motor = (current × resistance) which we call the "copper drop" This figure is very small and absorbs only a few per cent of the total, the rest of the voltage being absorbed in the rheostat since the back E M F. is nil. The rheostat is to be gradually cut out at such a rate that the current is kept uniform When the rheostat has been entirely cut out each motor is straight across the mains and receives the full line voltage, and the back E M F is then (line volts less copper drop).

Referring now to Fig 16, OF represents the full line voltage, which will be across the motor terminals when all the rheostat has been cut out Since the current during starting is to be considered uniform, there will be an equal copper drop at the beginning and end of the starting period, represented by OE and CB respectively. Join EC and OB.

Now at any given moment, for example at 10 seconds from the start, PQ represents the back E.M.F. of the motor, RQ the constant motor copper drop, and RS the voltage across the rheostats PS represents the line voltage, the sum of these three. It is therefore evident that OB is the curve of back E M F. and EC the rheostat voltage curve

Since the diagram refers to one motor and the current is kept uniform during starting, it follows that these voltages will be

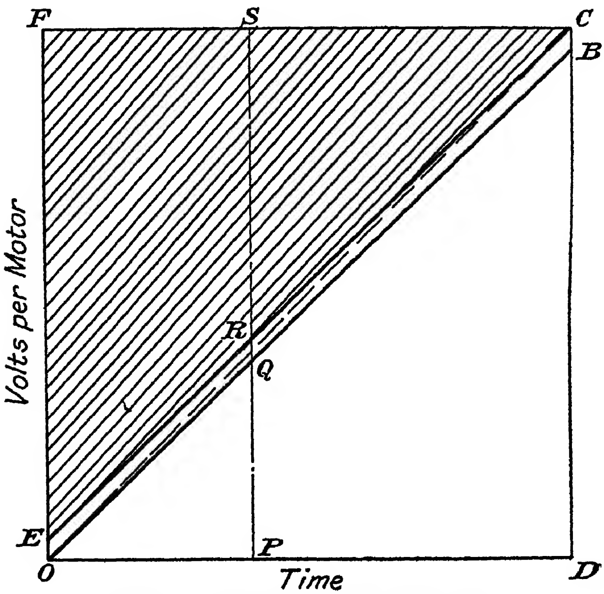


FIG. 16.—Plain Rheostat Starting.

proportional to watts expended, and the areas of the figures will represent energy in watt-seconds. The area of the figure OFCD represents energy supplied from the line per motor ; the area of the triangle OBD represents (back E.M.F. × current × time), i.e. the useful work done by the motor, or useful energy absorbed by the motor ; the area of OECB represents energy lost in the motor copper ; and the triangle EFC represents the energy lost in the rheostat.

Fig. 16 is drawn to scale for a particular motor, and it will be seen that the copper loss is in comparison almost negligible. If we agree to neglect the copper loss, then OE and CB need not be

put in and OC can be joined. It will then be evident that OFC = OCD.

i.e. rheostatic losses = energy used by motor,

and the efficiency of the starting process $= \dfrac{\text{energy used}}{\text{energy supplied}}$

$$= \frac{\text{OCD}}{\text{OFCD}} = 50 \text{ per cent.}$$

Series-Parallel Starting. Consider now the series-parallel case The motors will be first connected in series and then

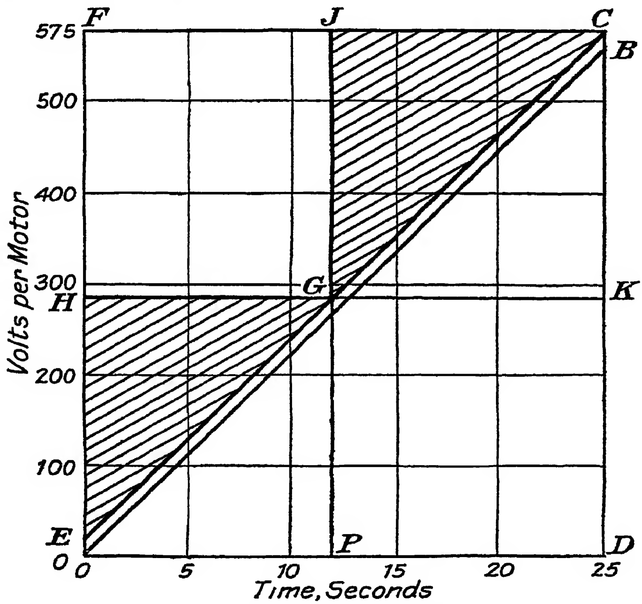


FIG. 17.—Series-Parallel Starting.

in parallel, the current per motor being assumed to be uniform throughout as before. The voltage across one motor and its rheostat will be half-line volts during the series period and full-line volts during the parallel period, as shown in Fig 17. OH = half-line volts and OF = line volts; OE and CB are the copper drop as before Join EC and OB G is the point at which GP, the voltage across the motor terminals (i.e. back E.M F + copper drop) reaches half-line volts, that is, it is the point of full

series, the volts per motor being absorbed in back E.M.F. and copper drop only, all the rheostat being cut out. Now pass into parallel, i.e. put the full line voltage across the motor and re-insert the rheostat. PJ becomes line voltage, and GJ the rheostat voltage, which falls as before to nothing at C, the point of full parallel.

The voltage lines as before can represent watts, and the energy from line per motor is now the area OHGJCD and the rheostatic losses the triangle EHG plus GJC. If as before the copper drop is neglected, G will intersect the line OC and the two triangles OHG plus GJC will be obviously half OFC. Hence the rheostat losses are half that of the plain rheostatic starting, i.e. rheostat losses $= \text{half power used, and efficiency} = \frac{\text{OCD}}{\text{OHGJC}} = \frac{2}{3} = 66\frac{2}{3}$ per cent.

Comparing the shaded area (rheostatic losses) with the shaded area in the previous case (Fig. 16), it is seen that the area HFJG has been saved by series-parallel starting, while the energy used by the motor is exactly the same in the two cases.

It will be seen that the time in series, HG, is slightly less than the time in parallel, GK, but that the two are equal if the copper drop be neglected. The construction of the diagram supplies a graphical method of determining these times exactly if required.

They can be readily calculated if preferred, thus :—

$$\frac{\text{series time}}{\text{total time}} = \frac{\text{HG}}{\text{FC}} = \frac{\text{EH}}{\text{EF}} \text{ (by similar triangles)}$$

$$= \frac{\text{OH}-\text{OE}}{\text{OF}-\text{OE}}$$

$$= \frac{\text{half line volts} - \text{copper drop per motor}}{\text{line volts} - \text{copper drop per motor}}.$$

Example. In the case of the L.N.W.R. train for which the run curve is worked out later on, to determine (1) the time in series and parallel, (2) the rheostatic losses, and hence (3) the efficiency of starting.

Resistance of motor (field, armature and interpoles) $= \cdot 0605$ ohm.

Average starting current $= 350$ amps.
Line voltage (assumed constant) $= 575$ volts.
Starting time (as calculated) $= 24\cdot 1$ secs.

Now copper drop per motor $= 350 \times \cdot 0605$
$= 21\cdot 2$ volts
$=$ OE or CB (Fig. 17)
OF $=$ Line volts
$= 575.$

Now EC is the curve of line voltage across the terminals of each motor. At starting there is only the copper drop of 21·2 volts, the rest EF being absorbed in rheostats At the finish the full line voltage is across each motor and none across the rheostats.

Set off OH = half-line volts (287·5), i.e voltage across one motor and its rheostat Draw HG horizontal to intersect EC at G. At G we have the full series position, each motor having across its terminals half line voltage. By measurement:

Time to reach full series = HG = 11·6 secs.

Time thence to full parallel = GK = 12·5 secs.

or by calculation $\dfrac{\text{series time}}{\text{whole time}} = \dfrac{\text{half line volts} - \text{copper drop per motor}}{\text{line volts} - \text{copper drop per motor}}$

$$= \frac{287 \cdot 5 - 21 \cdot 2}{575 - 21 \cdot 2} = \frac{266 \cdot 3}{553 \cdot 8} = \cdot 482$$

i e. series time = ·482 × 24·1 = 11·6 secs.
and parallel time = 24·1 — 11·6 = 12·5 ,,

Rheostatic losses = sum of triangles EHG and GJC, multiplied by starting current

$$= 350\left\{\left(\frac{266 \cdot 3 \times 11 \cdot 6}{2}\right) + \left(\frac{287 \cdot 5 \times 12 \cdot 5}{2}\right)\right\}$$

= 1,170 kilowatt secs per motor.

Total rheostatic losses for train (four motors) $= \dfrac{1{,}170 \times 4}{3{,}600}$

= 1·3 k.w hrs

Energy used by motor = area of back E.M.F. curve, i.e. triangle OBD.

$= \frac{1}{2} \times 24 \cdot 1 \times 553 \cdot 8 \times 350$
= 2,335 kilowatt secs. per motor.

Total energy used by train $= \dfrac{2{,}335 \times 4}{3{,}600}$

= 2·595 k.w. hours.

Energy supplied to each motor = area of curve of voltage across motor and resistance = area of figure OHGJCD × current per motor

$= 350\{(287 \cdot 5 \times 11 \cdot 6) + (575 \times 12 \cdot 5)\}$
= 3,680 kilowatt secs.

Total energy from line $= \dfrac{3{,}680 \times 4}{3{,}600}$

= 4·09 k w.h.

$$\text{Hence efficiency} = \frac{\text{energy used by train}}{\text{energy from line}} = \frac{2{\cdot}595}{4{\cdot}09}$$

$$= 63{\cdot}5 \text{ per cent.}$$

Compare this with the figure of 66·7 per cent. obtained by neglecting the copper drop.

It will occur at once to the student that the method might be extended to all four motors, i.e start all four in series, change over to series-parallel with two parallel circuits of two in series,

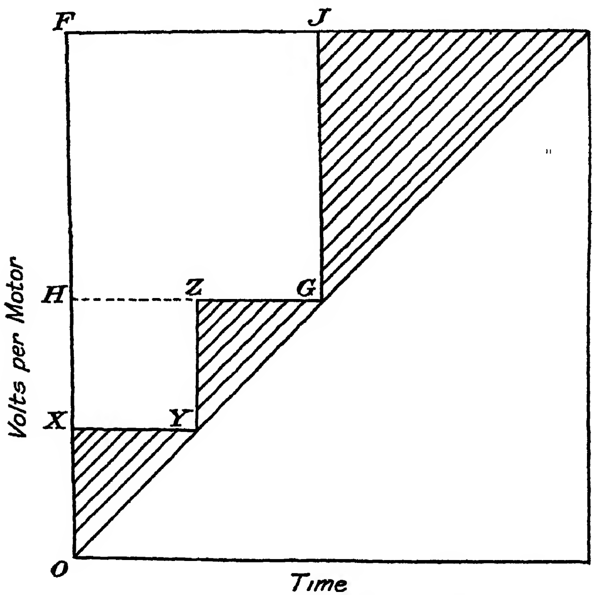


FIG. 18.—Double Series-Parallel Starting.

and finally full parallel. This is shown graphically in Fig. 18 in which for simplicity the copper drop has been neglected.

The diagram shows that the rheostatic losses from series-parallel are the same as for the parallel part of the usual two-motor method, the losses in series only having been halved. The whole rheostatic losses are thus reduced from $\frac{1}{2}$ to $\frac{3}{8}$ of the energy used by the motors, giving an efficiency of 72·7 per cent., as a brief consideration of the diagram will show. Thus HFJG shows the rheostatic loss saved by series-parallel starting, and XHZY the additional saving gained by double series-parallel.

The three methods may be summarized thus —

	Rheo losses	*Useful energy*	*Total energy supplied*	*Efficiency.*
Simple-Parallel	1	1	2	50%
Series-Parallel	$\frac{1}{2}$	1	$1\frac{1}{2}$	66·7%
Double Series-Parallel . .	$\frac{3}{8}$	1	$1\frac{3}{8}$	72·7%

Generally speaking the small additional energy saving does not counterbalance the extra cost and complication of switch gear involved Also a failure of a motor would put all four motors out of action, instead of only two. In locomotives, however, the double series-parallel control is often adopted on account of the advantage it offers of three economical running speeds, approximately a quarter, half and full speed respectively.

Transition. In any series-parallel arrangement there is evidently a point at which a transition must be made from series to parallel. Three methods are available for making this transition :—

(1) Open-circuit transition.
(2) Short-circuit transition.
(3) Bridge transition

(1) The first method is the simplest and consists in opening the circuit at full series while the re-arrangement of contactors is being made This system produces a violent jerk to the train (as may be felt in some London Tube trains) and naturally produces burning of the contacts which have regularly to break full load current. It may now be regarded as obsolete

(2) The short-circuit (or "shunt") method consists in accelerating to full series, inserting some resistance and short-circuiting one motor, afterwards opening the circuit at another point so that the two shall be in parallel. This is shown diagrammatically in its simplest form in Fig 19, where it is seen that one motor is completely short-circuited. Although a series motor on being short-circuited quickly loses its field flux, yet owing to residual magnetism there may be a heavy current generated and the alternative method of short-circuit transition shown in Fig. 20 is to be preferred. If the resistance of the rheostat during transition is graduated to a value suitable for the first parallel notch, then an excessive current flows through No. 2 motor while No. 1 is cut out, which may cause the wheels to slip This may not be of importance in multiple unit trains where there is an ample margin of adhesion, but is not allowable on locomotives. If, on the contrary, the resistance is made high to prevent this excessive current, then the first parallel notch is taken at too low a current

which causes a falling off of the acceleration during transition.

(3) The bridge method is best explained by referring to Fig. 21,

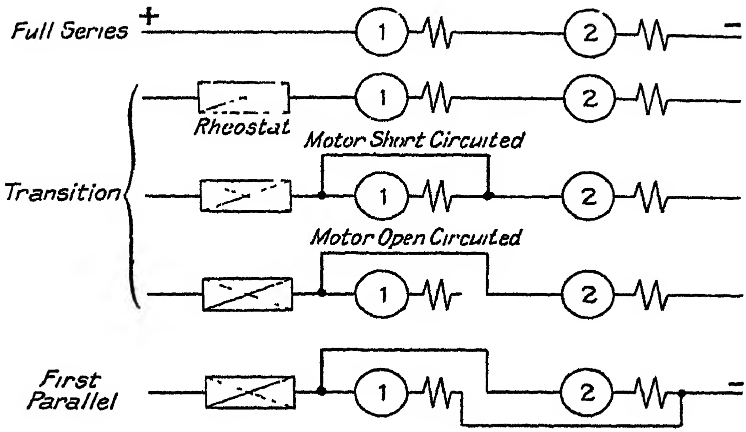


FIG. 19.—Short-Circuit Transition.

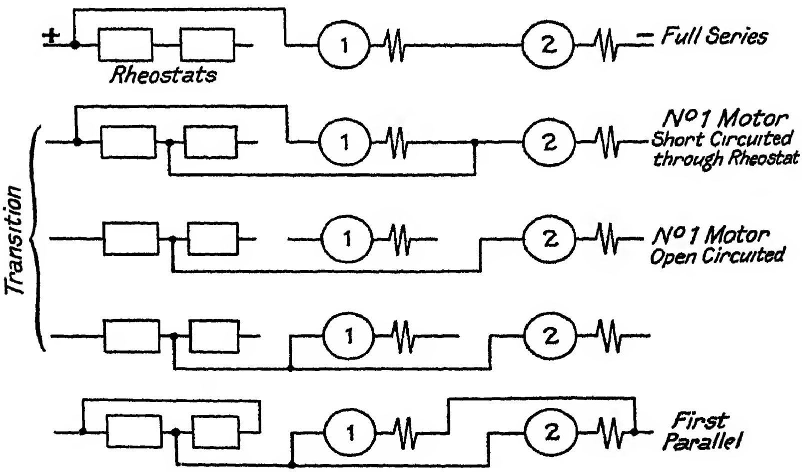


FIG. 20.—Short-Circuit Transition (alternative method).

which shows that in transition three conditions are happening simultaneously—the motors are in full series, each motor is in parallel with its rheostat, so that the two rheostats in series are straight across the line.

Bridge transition is widely used on multiple unit trains, since the automatic control which is generally used allows of the rheostats being adjusted to pass the full accelerating current to the motors during transition so that the bridge contactor does not normally break very much current

The current broken by the bridge contactor is always the

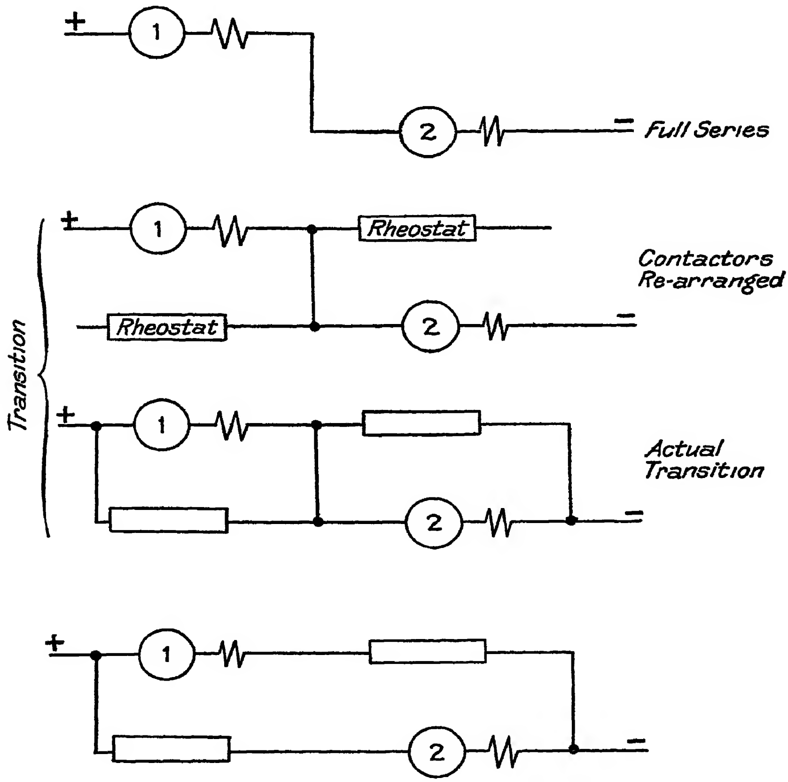


FIG 21.—Bridge Transition.

difference between that passing through the rheostat and that taken by the motors, which latter varies with the speed of the train at the moment of transition. In the case, therefore, of an interruption and restoration of current (caused, for example, by a gap in the conductor rail, a dead section, or the operation of a sub-station circuit breaker) causing the contactors to fall out

and pick up again rapidly, it is evident that the transition will be made with very small current on the motors, causing the bridge contactor to break a heavy current The bridge contactor must therefore be designed for this heavy duty Since, with the bridge transition, current to the motors is never interrupted nor a motor short-circuited, it is evidently the smoothest method of making transition.

It will be of interest to follow out a motor circuit diagram, e g. Fig 34, and to notice the arrangement of contactors to provide bridge transition

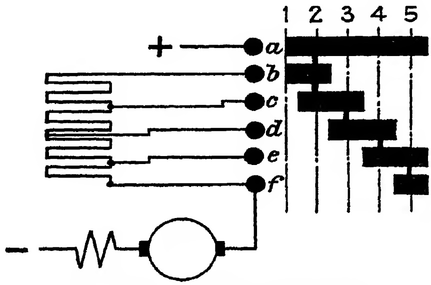


FIG. 22 —Simple Controller

Fig. 22 shows a simple controller for the control of one series motor operating in one direction of rotation. The controller drum is shown "developed," i.e spread out flat, the dotted lines indicating the controller notches. The rheostats and motor are shown connected to dots which represent contact fingers, and on any given notch the contact fingers are to be taken as sliding along to the corresponding dotted line. Thus on No. 3 notch current will enter at finger *a*, pass through the controller barrel and make contact with finger *d*, pass through sections *d* to *e* and *e* to *f* of the rheostat before reaching the motor. Controllers are always represented "developed" in this form.

BUILDING UP THE SPEED TIME CURVE

We have now covered the preliminary ground and are in a position to calculate the speed time curve for any given service from a knowledge of the train weights and the characteristics of the motor used. A designer, for instance, will have a knowledge of the performance of his particular motors, and will be given by a railway company a certain schedule to work to, stating the average length of run, gradients and curves, and any speed restrictions which may be imposed. From the curve then calculated the railway engineer can compute the power consumption, capacity of plant required in power- and sub-stations, and generally arrive at an estimate of costs

Now Fig. 23 shows a typical traction motor characteristic

curve, obtained on the test-bed at the maker's works, probably by the Hopkinson back-to-back method on two machines. The

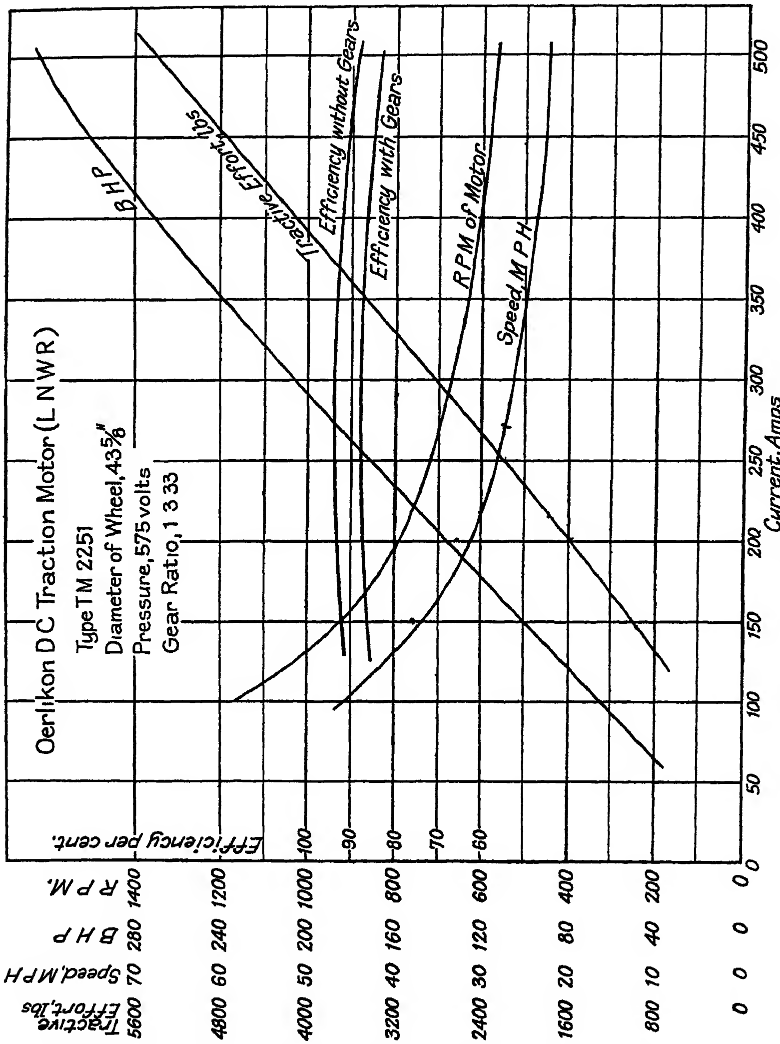


FIG. 23.

curve shown is that of the Oerlikon Co.'s motors supplied to the L. & N.W Railway trains running on the North London Railway and the Euston–Watford service.

It will be seen that the tractive effort curve is practically a straight line, i e. it varies proportionally to current, while the speed falls as current increases along a rectangular hyperbola. The method of building up the speed-time curve is the "point to point" method, and is best explained by working through an example. For the sake of simplicity and clearness many refinements are omitted, notably the variation of resistance with speed.

The run selected is the following .—

L. & N W.R. 3-coach train running empty from Stonebridge Park to Harlesden, level track, a distance of 4,950 ft. Dead weight of train 112 tons. Effective weight 12 per cent. above dead weight Average accelerating current 350 amps. Braking rate 2 m p h p s. Train resistance assumed constant at 5 lbs per ton of dead weight during acceleration and 6 lbs. per ton during coasting. Time of run is to be 2 mins. 27 secs.

PROBLEM —Construct the complete run curve for the trip.

Now throughout we shall deal with the performance of one motor, assumed to be doing its share of the load.

$$\text{Effective weight} = 1{\cdot}12 \times 112 = 125{\cdot}5 \text{ tons}$$
$$= 31{\cdot}4 \text{ tons per motor.}$$

$$\text{Train resistance per motor} = \frac{112 \times 5}{4}$$
$$= 140 \text{ lbs.}$$

Now from motor characteristic curve, Fig. 23, tractive effort corresponding to 350 amps. is 3,450 lbs.

Train resistance	140 ,,
Net tractive effort	3,310 ,,

$$\text{Resulting acceleration will be } a = \frac{F}{102W} = \frac{3{,}310}{102 \times 31{\cdot}4}$$
$$= 1{\cdot}03 \text{ m.p.h. per sec.}$$

Referring again to curve, speed corresponding to 350 amps. is 24·8 m.p h. Since $v = at$, $t = \dfrac{v}{a} = \dfrac{24{\cdot}8}{1{\cdot}03}$,

$$= 24{\cdot}1 \text{ secs.}$$

This gives us the *first point* on the curve, a straight line acceleration to 24·8 m p.h. in 24·1 secs.

Take now a small increment of speed, say to 27·5 m.p.h , an increment of 2·7 m.p.h.

Now referring again to the motor curve find 27·5 m.p.h. on

the speed line, and project downwards to cut the tractive effort curve at a point which must be read off on the tractive effort scale The tractive effort corresponding to 27·5 m.p.h. will be found

	$=$ 2,378 lbs.	
Train resistance	$=$ 140	,,
Net tractive effort	$=$ 2,238	,,

So the net tractive effort over this small interval was 3,310 lbs at the start, and 2,238 lbs. at the finish.

$$\therefore \text{ Average tractive effort over interval} = \frac{3{,}310 + 2{,}238}{2} = 2{,}774 \text{ lbs.}$$

$$\text{Resulting average acceleration over interval} = \frac{2{,}774}{102 \times 31{\cdot}4} = {\cdot}866 \text{ m.p.h. per sec.}$$

$$\text{Time for interval} = \frac{2{\cdot}7}{{\cdot}866} = 3{\cdot}12 \text{ secs.}$$

$$\text{Time from start} = 3{\cdot}12 + 24{\cdot}1 = 27{\cdot}2 \text{ secs.}$$

So that a speed of 27·5 m.p.h is reached in 27·2 secs., and thus we have the *second point* on our curve.

Take a further increment to 30 m.p h., i e. an increment of 2·5 m.p.h.

Corresponding tractive effort is	1,775	lbs.
Resistance	140	,,
Net tractive effort	1,635	,,

$$\text{Average tractive effort over the interval} = \frac{2{,}238 + 1{,}635}{2} = 1{,}937 \text{ lbs.}$$

$$\text{Average acceleration over interval} = \frac{1{,}937}{102 \times 31{\cdot}4} = {\cdot}605 \text{ m p h. per sec.}$$

$$\text{Time for interval} = \frac{2{\cdot}5}{{\cdot}605} = 4{\cdot}13 \text{ secs.}$$

Time from start $= 4{\cdot}13 + 27{\cdot}2 = 31{\cdot}3$ secs., giving the *third point* on the curve.

A further two points have been taken and the whole tabulate for clearness as follows :—

Speed m p h.	Speed Increment. m p h.	Net Tractive Effort lbs	Mean Tractive Effort. lbs	Mean Acceleration. m p h p s.	Time Increment secs.	Time from Start secs
0		3,310				
	24 8		3,310	1·03	24 1	
24·8		3,310				24 1
	2 7		2,774	·866	3 12	
27 5		2,238				27 2
	2 5		1,937	·605	4 13	
30		1,635				31 3
	5		1,328	·416	12 02	
35		1,020				43 3
	5		805	·252	19 8	
40		590				63·1

From the first and last columns the curve shown in Fig 24 is plotted. At 147 seconds the braking curve is drawn in, corre-

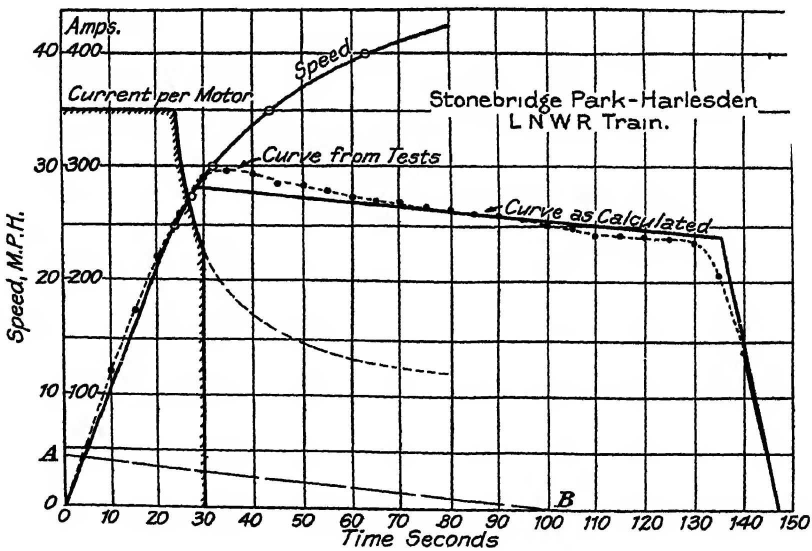


FIG. 24.

sponding to 2 m p h. per sec. The coasting slope AB corresponding to 6 lbs per ton is also drawn in anywhere. It is necessary

to place the actual coasting line, which must be parallel to AB, so that the complete run curve encloses an area equivalent to the distance, 4,950 ft

E g. If we take for our scale 1 inch = 10 miles per hour, and 1 inch = 25 secs. Then 1 sq. inch $= \dfrac{10 \times 5{,}280 \times 25}{3{,}600}$

$$= 366{\cdot}5 \text{ ft.}$$

Hence curve area must be $\dfrac{4{,}950}{366{\cdot}5} = 13{\cdot}5$ sq. in.

The method is one of trial and error, but with a planimeter the correct place can usually be found after two or three are tried. The figure shows the final result

In working any point-to-point method it must be remembered that a small error in one point added to a small error in the next may aggregate finally to a considerable error, and working should be checked on each point before proceeding to the next. Evidently, too, the smaller the increments chosen the greater the accuracy.

When the student has read Chapter XI on train resistance, he will realise that the train resistance cannot be taken as constant throughout but varies with each value of the speed. In the working above the assumption of constancy has been made for the sake of simplicity, and to keep the outline of the method clearly before the student ; and that the error for low speeds and short distances is not great is proved by the dotted curve, which is drawn from 5-second readings taken with a speedometer and stop-watch over this same run. The closeness of the two curves shows how nearly theory agrees with practice in this case.

Current Curve. When reading off the tractive resistance for various speeds from the motor characteristic curves the current may also be read off. The following figures will be obtained :—

Speed (m p h).	*Time from Start (secs).*	*Current (amps.)*
24·8	24·1	350
27·5	27·2	265
30	31·3	216
35	43 3	164
40	63·1	128

These values are shown on Fig. 24 which gives the current curve to a time basis. The etched curve shows the actual current curve for the run, a steady value of 350 amps. up to 24 1 secs., then falling along a hyperbolic curve during the free running

period and falling to zero at the point of cut-off. The dotted line shows the continuation of the curve as it would have been if power had not been cut off.

A speed-time curve constructed as described is capable of giving a very great deal of information as to the performance of the train under average conditions in service. There may be cases, however, in which the speed-time curve for a particular run is required, taking into consideration grades and curves, and since there is no mathematical connection between speed and current the speed at any particular current can only be found by a process of trial and error. As before, an example is the best method of explanation.

Taking the same train data as in the last example, to draw the speed-time curve for a 5,000 ft. run with curves and gradients shown in Fig. 25. Train resistance is to be read from the curve for a 3-car train shown in Fig. 122. Time of run is to be 130 secs.

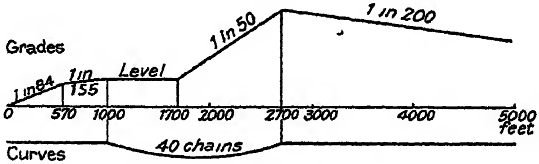


FIG. 25.—Profile of Track.

Now evidently this run must be divided up into sections, a new section being necessary every time the curve or grade changes. The first section is an up grade of 1 in 84, which represents a downhill pull of

$\frac{112}{84} = 1{\cdot}335$ tons $= 0{\cdot}33$ tons per motor $= 740$ lbs. per motor

At 12 m.p.h. resistance is 6 lbs per ton (Fig. 122) Train resistance $= 168$ „ „ „

Total $= 908$ „ „ „

Net tractive effort is $3{,}450 - 908$ $= 2{,}542$ lbs. per motor

Resulting acceleration will be

$$a = \frac{F}{102W_e} = \frac{2{,}542}{102 \times 31{\cdot}4} = 0{\cdot}8 \text{ m p.h per sec.}$$

$$\text{Time taken to reach } 24{\cdot}8 \text{ m p.h.} = \frac{24{\cdot}8}{0{\cdot}8} = 31 \text{ secs.}$$

$$\text{The distance travelled will be } \tfrac{1}{2} \times 24{\cdot}8 \times \frac{88}{60} \times 31 \text{ ft.} = 564 \text{ ft.}$$

This is near enough to the 570 ft. of the first section, and gives the first point on the curve The distance-time curve should also be plotted at the same time, as shown on Fig. 26

Take now a speed increase to 27·5 m.p.h., an increment of 2·7 m.p h. Up grade is now 1 in 155 = 404 lb. per motor.

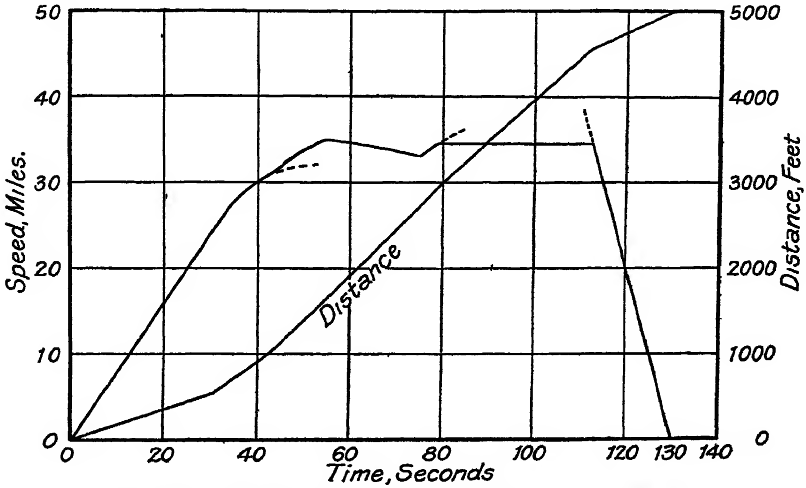


FIG. 26.—Speed-Time Curve for run shown in Fig. 25.

From Fig. 122 resistance at mean speed

i.e. at 26·15 m p h.	= 8·5	lbs. per ton
	= 238	lbs. per motor
Up gradient	= 404	,, ,, ,,
Total	= 642	,, ,, ,,

$$\text{Mean net tractive effort} = \frac{3{,}450 + 2{,}378}{2} - 642 \text{ lbs.}$$
$$= 2{,}272 \text{ lbs.}$$

$$\text{Resulting average acceleration} = \frac{2{,}272}{102 \times 31{\cdot}4} = 0{\cdot}71 \text{ m p.h. per sec.}$$

Time taken over speed increment $= \frac{2{\cdot}7}{{\cdot}71} = 3{\cdot}8$ secs. Total time = 34·8 secs.

Distance travelled over speed increment $= 26{\cdot}15 \times \frac{88}{60} \times 3{\cdot}8$ = 146 ft. Total distance = 710 ft.

The slope of the distance curve suggests that the train will reach 30 m p h. before coming to the end of the second section.

Taking a speed increase to 30 m p h

Train resistance at mean speed—

$$\begin{aligned} \text{i.e at } 28{\cdot}75 \text{ m p.h} &= 9{\cdot}1 \text{ lbs. per ton} \\ &= 255 \text{ ,, per motor} \\ \text{Up gradient} &= 138 \text{ ,, ,, ,,} \\ \text{Total} &= \underline{\underline{393}} \text{ ,, ,, ,,} \end{aligned}$$

$$\text{Mean net tractive effort} = \frac{2{,}378 + 1{,}775}{2} - 393 \text{ lbs.}$$
$$= 1{,}684 \text{ lbs.}$$

$$\text{Average acceleration} = \frac{1{,}684}{102 \times 31{\cdot}4} = 0{\cdot}526 \text{ m p h. per sec.}$$

$$\text{Time taken} = \frac{2{\cdot}5}{{\cdot}526} = 4{\cdot}7 \text{ secs. Total time} = 39{\cdot}5$$
secs.

$$\text{Distance travelled} = 28{\cdot}75 \times \frac{88}{60} \times 4{\cdot}7 = 198 \text{ ft.}$$
$$\text{Total distance} = 908 \text{ ft.}$$

The shape of the curves now suggests that the 1,000 feet will be reached at about 32 m.p.h. Trying this, we have :—

$$\begin{aligned} \text{Train resistance at mean speed 31 m.p h.} &= 9{\cdot}7 \text{ lbs. per ton} \\ &= 272 \text{ ,, per motor} \\ \text{Up gradient} &= 138 \text{ ,, ,, ,,} \\ \text{Total} &= \underline{\underline{410}} \text{ ,, ,, ,,} \end{aligned}$$

$$\text{Mean net tractive effort} = \frac{1{,}775 + 1{,}460}{2} - 410 \text{ lbs.}$$
$$= 1{,}208 \text{ lbs.}$$

$$\text{Average acceleration} = \frac{1{,}208}{102 \times 31{\cdot}4} = 0{\cdot}38 \text{ m.p.h.}$$

$$\text{Time taken} = \frac{2}{{\cdot}38} = 5{\cdot}3 \text{ secs. Total time} = 44{\cdot}8 \text{ secs.}$$

$$\text{Distance travelled} = 31 \times \frac{88}{60} \times 5{\cdot}3 = 241 \text{ ft.}$$
$$\text{Total distance} = 1{,}149 \text{ ft.}$$

This distance is greater than 1,000 ft , showing that the estimate of 32 m p h for the speed at that distance was too great. By plotting the points just obtained, however, it is seen that at

1,000 ft. the corresponding speed will be 31 m.p h., and the total time 42·5 secs

We now come to a level stretch with a curve of 40 chains. As stated in Chapter XI, the extra resistance in lbs. per ton due to a curve is

$$\frac{63{\cdot}6}{\text{radius in chains}}$$

For a 40-chain curve it is therefore

$$\frac{63\ 6}{40} = 1{\cdot}6 \text{ lbs per ton} = 45 \text{ lbs. per motor.}$$

Take now a speed increase to 33 m.p h

Train resistance at mean speed 32 m p h	= 10	lbs	per ton
	= 280	,,	per motor
Curve resistance	= 45	,,	,, ,,
Total	= 325	,,	,, ,,

$$\text{Mean net tractive effort} = \frac{1{,}600 + 1{,}360}{2} - 325 \text{ lbs.}$$
$$= 1{,}155 \text{ lbs.}$$

$$\text{Average acceleration} = \frac{1{,}155}{102 \times 31{\cdot}4} = 0{\cdot}36 \text{ m p.h. per sec.}$$

$$\text{Time taken} = \frac{2}{{\cdot}36} = 5\ 6 \text{ secs. Total time} = 48{\cdot}1 \text{ secs.}$$

$$\text{Distance travelled} = 32 \times \frac{88}{60} \times 5{\cdot}6 = 263 \text{ ft. Total dis-}$$

tance = 1,263 ft.

To reach 1,700 ft., the slope of the curve suggests a speed of 35 m p h. at this point.

Train resistance at 34 m p h	= 10·5	lbs.	per ton
	= 294	,,	per motor
Curve resistance	= 45	,,	,, ,,
Total	= 339	,,	,, ,,

$$\text{Mean net tractive effort} = \frac{1{,}360 + 1{,}160}{2} - 339 \text{ lbs.}$$
$$= 921 \text{ lbs.}$$

$$\text{Average acceleration} = \frac{921}{3{,}200} = 0{\cdot}29 \text{ m.p h per sec}$$

$$\text{Time taken} = \frac{2}{{\cdot}29} = 6{\cdot}9 \text{ secs Total time} = 55{\cdot}0 \text{ secs.}$$

$$\text{Distance travelled} = 34 \times \frac{88}{60} \times 6{\cdot}9 = 344 \text{ ft. Total dis-}$$

tance = 1,607 ft.

This is near enough for the distance to be plotted, the curve produced to the 1,700 ft. desired, at which point the speed will be 35·2 m p.h. and the time 56 secs.

We now encounter, in addition to the curve, a gradient of 1 in 50, i e a downward pull of 1,255 lbs per motor Since this is more than the tractive effort, the speed will evidently fall. We shall therefore try a fall of speed to 33 m p h.

Train resistance at 34·1 m p h.

= 10·55 lbs. per ton =	295	lbs. per motor
Curve resistance =	45	,, ,, ,,
Up gradient =	1,255	,, ,, ,,
Total =	1,595	,, ,, ,,

Mean tractive effort at 34·1 m p.h = 1,250 lbs
Net mean tractive effort = 1,250 — 1,595 = — 345 lbs

Average deceleration $= \frac{345}{3{,}200} = \cdot 108$ m p.h per sec.

Time taken $= \frac{2\cdot 2}{\cdot 108} = 20\cdot 4$ secs. Total time = 76·4 secs.

Distance travelled $= 34\cdot 1 \times \frac{88}{60} \times 20\cdot 4 = 1{,}020$ ft. Total distance = 2,720 ft.

This is a sufficiently close approximation to 2,700 ft., and the rest of the run is a down grade of 1 in 200 without a curve.

The speed will now increase. Take a speed increase to 35·2 m.p.h.

Train resistance at 34·1 m.p h =	295	lbs. per motor
Down grade =	314	,, ,, ,,
Net excess =	19	,, ,, ,,

Mean tractive effort at 34·1 m.p h. = 1,250 lbs.
Net mean tractive effort = 1,250 + 19 = 1,269 lbs

Average acceleration $= \frac{1{,}269}{3{,}200} = \cdot 397$ m p.h. per sec.

Time taken $= \frac{2\cdot 2}{\cdot 397} = 5\cdot 5$ secs. Total time = 81·9 secs.

Distance travelled $= 34\cdot 1 \times \frac{88}{60} \times 5\cdot 6 = 280$ ft Total distance = 3,000 ft.

Take speed increase to 40 m.p h

Train resistance at 37·6 m p h.

$$= 11{\cdot}5 \text{ lbs per ton} = 322 \text{ lbs. per motor}$$
$$\text{Down grade} = \underline{314} \;\;,, \;\;,, \;\;,,$$
$$\text{Net resistance} = \underline{\underline{8}} \text{ lbs. per motor.}$$

Mean tractive effort at 37 6 m p h = 925 lbs.
Net mean tractive effort = 925 — 8 = 917 lbs

$$\text{Average acceleration} = \frac{917}{3{,}200} = {\cdot}287 \text{ m.p h per sec}$$

$$\text{Time taken} = \frac{4\ 8}{287} = 16\ 7 \text{ secs} \quad \text{Total time} = 98{\cdot}6$$
secs

$$\text{Distance travelled} = 37{\cdot}6 \times \frac{88}{60} \times 16\ 7 = 920 \text{ ft.} \quad \text{Total}$$
distance = 3,920 ft.

It would now appear that coasting and braking curves can be put in Braking is to be at 2 m p h. per sec. as before, and its curve can be drawn in from the end of the run, which is to be 130 seconds. It may be said with some certainty that the coasting will take place on the 1 in 200 down grade If the average coasting speed is estimated at 35 m p h , the train resistance will be 10 8 lbs. per ton. Allowing an extra 5 per cent. for gear friction, the amount becomes approximately 11·35 lbs. per ton

$$= 318 \text{ lbs. per motor.}$$
$$\text{Then tractive effort due to down gradient} = \underline{314} \;\;,, \;\;,, \;\;,,$$
$$\text{Net retarding force} = \underline{\underline{4}} \text{ lbs. per motor.}$$

Thus the force due to gravity almost exactly balances that due to resistance, and the train coasts at a uniform speed of 35 m p h

By using the planimeter as in the previous example, it is found that to the scale chosen, i e 1 in = 10 m p h. and 1 in. = 20 secs.

$$\text{Then 1 sq. in} = 10 \times \frac{88}{60} \times 20 \text{ ft} = 293 \text{ ft.}$$

Since the total distance is 5,000 ft., the area of the complete run must be $\frac{5000}{293} = 17{\cdot}1$ sq ins.

It will be found that the area with 35 m.p h. coasting is slightly too high. A second trial will show that the correct speed is very

nearly 34·6 m p h The curve is thus completed and the distance curve should also be calculated in the same manner as before, and drawn in.

It will be seen that this point to point method becomes very laborious when a number of curves have to be drawn and a more rapid method of calculating such curves has been devised by Mr F. W Carter * and is set out fully in his recent book,† depending upon the assumption of an algebraical expression for the relationship of speed and tractive effort

In any case the labour involved in calculating out complete run curves for each station to station run is very great but is more than repaid by the advantages and economics which can be made by the possession of exact knowledge of the capacity and performance of the trains.

* *Transactions of the American Institute of Electrical Engineers,* Vol. 22, p 113.

† *Electric Railway Traction,* by F. W. Carter. (Edward Arnold & Co)

CHAPTER IV

CONTROL SYSTEMS

Direct Control. When electric traction was first applied to railway trains the form of control used was the Direct Control. In this system the control of the motors is directly effected by a controller which handles the main motor current as in the case of most tram-cars In order to drive the train from either end cables must be provided to interconnect the controllers, and the number of these heavy cables will be large if reversing is also to be done in the controller. By using a remote-controlled reversing switch the number of heavy cables may be reduced to four, but it is necessary to duplicate the starting rheostats, using at any one time only those on the coach from which the train is being driven

This system of control is still in use on the Liverpool–Southport section of the Lancashire and Yorkshire Railway. The trains consist of one or two motor coaches and a number of trailers, and the system allows of controlling two motor coaches only per train.

As the size and length of trains increased, however, these controllers became large and heavy to operate manually, and the next development was a large controller operated not by hand but by power The Mersey Railway still uses large controllers of this type operated by a pneumatic cylinder which is electrically controlled.

The increase in size and weight of such controllers and the unsatisfactory nature of the means they afford for breaking large currents induced engineers to search for a more suitable system, which would also permit of greater flexibility in the "make-up" of the trains so that any number of cars could be readily coupled together and operated from one master controller. This arrangement, called the Multiple Unit System, was introduced by Sprague in conjunction with the General Electric Co. of America.

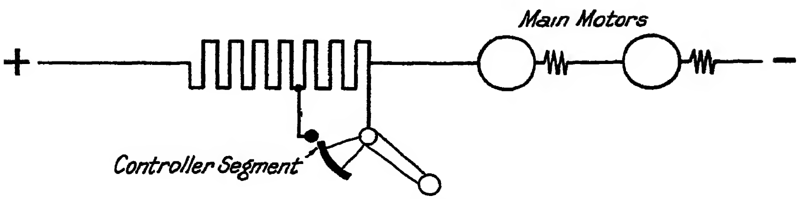
The Multiple Unit System

This system, which is now universally adopted in some form or other, consists essentially of fitting remote-controlled switch-gear on each motor coach to control the operation of the motors on that coach, the switch-gear on any number of motor coaches being controlled from any small master controller on the train. The main power circuits to the motor are not connected to but are electrically separate from the control circuit, and indeed often operate on an entirely different voltage On coupling together a number of such coaches with or without trailers, the control circuits carrying a few amperes only are electrically coupled together, and the train is operated as a whole from any one controller. The flexibility of such a system is obvious, as any one will realise who sees a train come into a terminal station, couple up to a train standing in the station and start out again loaded with passengers within a few minutes of arrival. Furthermore, whatever length of train is thus made up the driving power per ton remains constant, so that the schedule speed can be maintained by trains made up of any number of coaches.

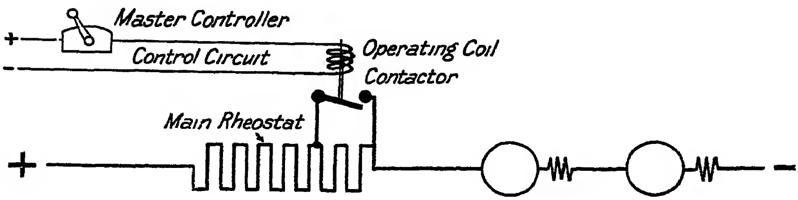
Forms of Multiple Unit Control. To satisfy the requirements of the multiple unit system, any form of power can be used to operate the switches and contactors on the car. The motive force for closing such contactors on each motor car may be (1) electro-magnetic, (2) pneumatic, (3) mechanical, i.e. a cam-shaft operated either by a pneumatic engine or electric motor. Whichever of these is used the operating force is finally controlled electrically from the master controller.

It will be seen that when, as in all multiple unit systems the rheostat sections are to be short-circuited by means of contactors, the power used to close such contactors represents merely a link between the master control circuit and the main power circuit, the form of link used, i e magnetism, air pressure or mechanical force, being unimportant This is shown clearly in Fig 27, in which a single sample resistance step is shown closing by (*a*) a direct controller, (*b*) electro-magnetic contactor, (*c*) air-operated contactor, (*d*) electric motor or air operated cam. The contactor coils of system (*b*) may be operated either by the line voltage or by a lower voltage supplied by a motor generator from the line voltage or from batteries

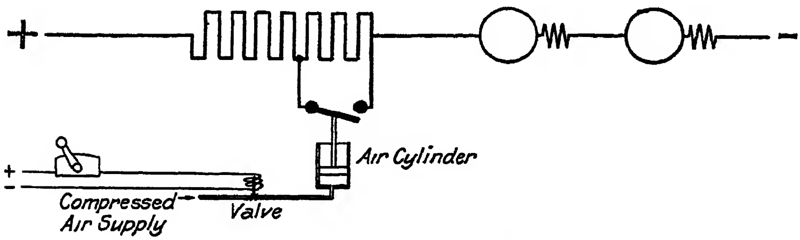
The first modification of the direct controller was the motor-driven controller which allowed of small master controllers being used and satisfied the requirements of multiple unit working.



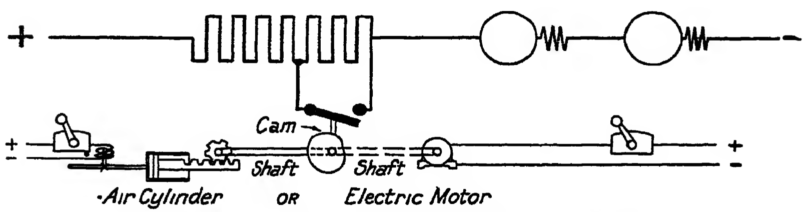
Direct Control.



Electro-magnetic Contactors.



Electro-pneumatic Contactors.



Camshaft, Pneumatic, or Electric Motor Driven.

Fig. 27.—Types of Control Systems.
One sample contactor shown in each case.

But the arrangement of contacts mounted on a revolving barrel, making and breaking contact with a number of fingers, is difficult to fit with a quick break action and an effective blow-out, and the individual contactor system was therefore resorted to. This was first operated electro-magnetically and still survives in general use The advantage of compressed air for the operation of contactors is the ease with which a considerable mechanical force can be obtained on the contacts, which enables smaller and lighter contacts to be used Against this advantage must be set the risk of freezing up of valves in cold weather, due to water being carried over with the air

The complexity of interlocks for obtaining automatic working and for ensuring the correct sequence of contactors is the chief cause of the development of the cam-shaft control in which correct sequence is ensured mechanically.

Before describing an example of each of these systems it may be well to mention a few features common to them all, which are peculiar to electric train operation.

Hand and Automatic Control—Current Limit Relay. In a multiple unit system designed for hand control, the contact segments in the master controller making contact with the various fingers complete the circuits which operate the actual control gear on each car In other words, if the motor-man puts the controller to any particular notch the control gear immediately follows to the arrangement corresponding to that notch, and the train may be brought up to speed slowly or quickly at the will of the driver.

In automatic control, on the other hand, the motor-man can bring his controller handle round to full parallel at once, the control gear on each coach following point by point as regulated by the current-limit relay This relay is governed by the motor current, which again depends on the speed of the train, so that the effect of the use of this relay is to take the rate of acceleration of the train out of the hands of the driver and allow it to be regulated automatically and uniformly. The relay consists essentially of a solenoid carrying a few turns of heavy section copper which is permanently in series with the main motor current of the particular coach This solenoid is fitted with a plunger which in its de-energised position makes a bridge contact across two terminals through which is passing the control current to operate the due sequence of the contactors, as shown diagramatically in Fig 28. On starting the train the current rushes up to a certain value, for instance 400 amps, which rapidly

decreases as the train gathers speed. The effect of this heavy current is to lift the plunger and break contact in the control circuit, and the plunger remains held up until the current falls to some predetermined value, e g 350 amps.

The plunger is loaded either by a weight or by a spring and is arranged so that the cutting-in value is adjustable. As soon, therefore, as the speed of the train has allowed the current to fall to 350 amperes the plunger falls and again makes contact, completing that part of the control circuit and allowing the main control gear to cut out another section of the power rheostat. The current again jumps up to a momentary value of 400 amps , the plunger rises and the whole cycle of operations is repeated, until the train is up to full speed. If the motor-man brings his handle round to any given notch, the main control gear, whether electromagnetic, pneumatic or otherwise, will automatically build up to that point. The acceleration of the train is entirely governed by the current limit relay, notching or accelerating relay as it is variously called, which is adjustable to any desired range within the capacity of the motors

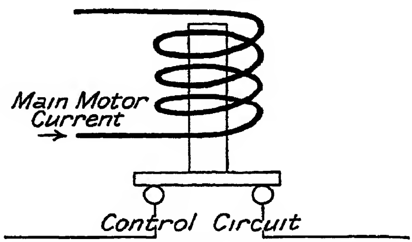


FIG. 28 —Principle of Current Limit Relay.

This arrangement naturally promotes uniformity and smoothness of starting, avoids jerks to passengers and equipment, and tends towards a low energy consumption and small heating of motors , further it relieves the motor-man of all need for thought or care for passengers and equipment at starting, and allows him to devote his entire attention to his primary duties of driving the train On an up gradient or with a heavily loaded train the current will fall more slowly and the relay will ensure that a longer time is allowed between notches, thus protecting the equipment and reducing the rate of acceleration, while on a down gradient the acceleration will be more rapid, current will fall quickly and the relay will allow a quicker rate of notching up. In all cases, therefore, the relay ensures that the starting current on the various controller points is kept between predetermined limits, while the rate of acceleration is allowed to vary according to the gradient or load It can, however, present certain dangers. If the wheels should slip owing to snow on

the rail or when starting on a severe up gradient, the current immediately falls and the succeeding points of the controller are taken as rapidly as the time elements in the controller or relay will permit, thus tending to increase the slipping of the wheels. The only cure is to shut off power and start up again. This relay is therefore more suited for use on trains in which the motive power is distributed over a number of axles, since the tractive effort on such wheels is usually well below the limit of adhesion. In electric locomotives, for example, the motive power is concentrated on a few wheels working much nearer to the limit of adhesion and it is often desired to regulate the starting current to suit the gradient and load, which latter varies to a much greater extent than is the case with motor coach trains. Also the driver of a locomotive is necessarily a man of more skill and experience than is needed for driving ordinary suburban passenger trains, and such a man can be trusted to safeguard the operation of the train without the need of a "fool-proof" relay.

Some American railroads employ light cars, i e. cars having a low ratio of tare weight to passengers carried, and it is thought advisable to regulate the setting of the current limit relay according to the loading An example of this is found on the Brooklyn Rapid Transit Company's cars, in which the relay setting is mechanically increased by leverage from the bolster as the passenger loading causes the springs to deflect. This nicety of adjustment conflicts with the British preference for simplicity, and so is not found in Great Britain

An illustration of an actual current limit relay is given in Fig. 29 which shows the General Electric (U.S A) or British Thomson-Houston Company's relay as fitted to their electro-magnetic Type "M" automatic control, used on the District Railway and tube railways of London, some trains on the North-Eastern Railway, the Victorian Railways (Australia), Central Argentine, and many lines in the United States. The Westinghouse (Metropolitan-Vickers) system used on the London and South-Western Railway is similar in principle to the General Electric Type "M" and employs a current limit relay of very similar design.

The main series coil is seen to be the middle of the three coils shown in Fig. 29, and carries the current of one motor. The outer coils are shunt coils in series with the energising coils of the contactors, in such a manner that if one contactor coil is energised in series with one shunt coil, the next contactor coil

to close will be energised in series with the other shunt coil. Each plunger in its lowest position bridges by its disc two contacts in the circuit of the coil of the other so that both cannot be energised at the same time. The magnetic circuit of the relay is seen to be such that either plunger when raised is held up by the main current coil, which retains it in the raised position

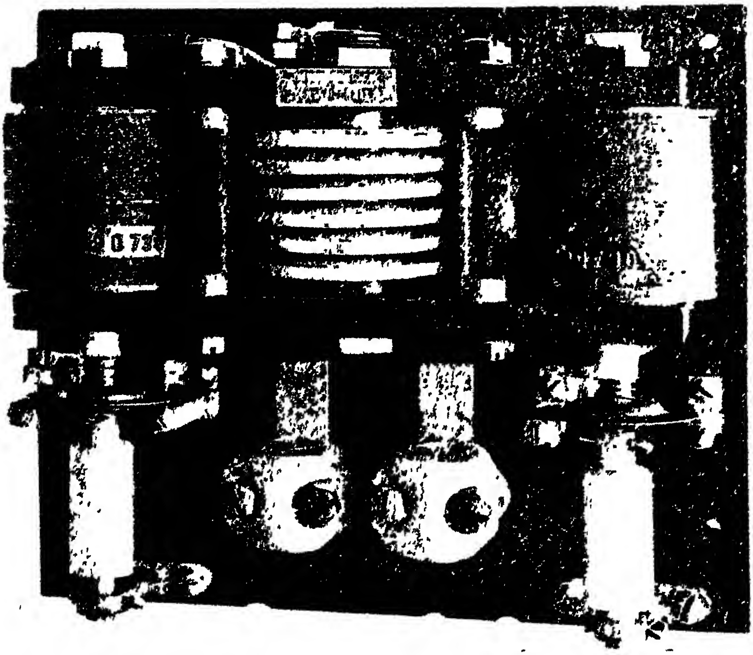


FIG. 29 —Notching Relay for Automatic Control

(its shunt coil circuit having been opened by the closing of the contactor) until the current has dropped to the predetermined value.

The general method of operation is as follows As each contactor closes, it transfers its operating coil from a lifting to a holding circuit, opening also the connection with the first current limit relay shunt coil The next contactor is now ready to be energised in series with one of its own interlocks and with the second relay shunt coil, thus allowing the contactor to be energised as soon as the motor current has diminished sufficiently

to allow the relay to operate and close the contacts below to the second relay coil. Fig 30 shows a diagram from which these operations can be traced out The interlock contacts are carried on a rod actuated by a lever from the contactor plunger It will be seen from this diagram that each contactor requires four pairs of interlocks, which gives an idea of the number of small contacts on which the operation of the control system depends

An adjustable time-lag device of the dash-pot type is fitted to each plunger. This enables the operation of the shunt coil plungers to be made uniform and is also of use in "running the controller round" with the circuit breakers open, to test the control gear while the train is stationary, since without it

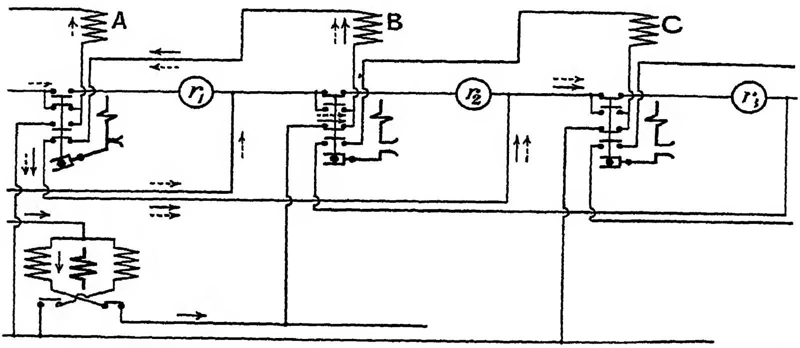


FIG. 30.—Diagram of Succession in Automatic Relay Control (Full lines show closing circuit for Contactor B, Contactor A being closed. Broken arrows show holding circuit for Contactor B, after closing)

the contactors would follow each other very rapidly. It also prevents the plungers from striking too hard a blow on the contacts. The nut which can be seen in the illustration above the series coil provides the necessary adjustment for setting the relay, allowing the air gap between the two halves of the coil to be suitably varied

The Dead Man's Handle. Steam locomotives invariably carry a crew of two, a driver and a fireman, so that in the event of sudden illness of the driver there is another man in reserve to stop the train In the case of electric trains, however, one motor-man only is necessary, and it therefore becomes essential to provide a safety device in case of sudden incapacity of the driver. A device called the Dead Man's Handle or Button is provided which is held depressed against a spring by the driver's

hand all the time he is driving If for any cause he should take his hand off the controller handle, the dead man's "button" is forced up by the pressure of the spring and has the effect of instantly opening a switch which carries the control circuit, thereby cutting off power and at the same time applying brakes with emergency power, thus stopping the train in the shortest possible time. The "button" may be a piece projecting through the driver's handle, or the handle itself may be hinged at the end and require holding down as is seen in Fig 31. When the Dead Man's Handle has once operated it must be brought back to the "off" position before the train can be again started.

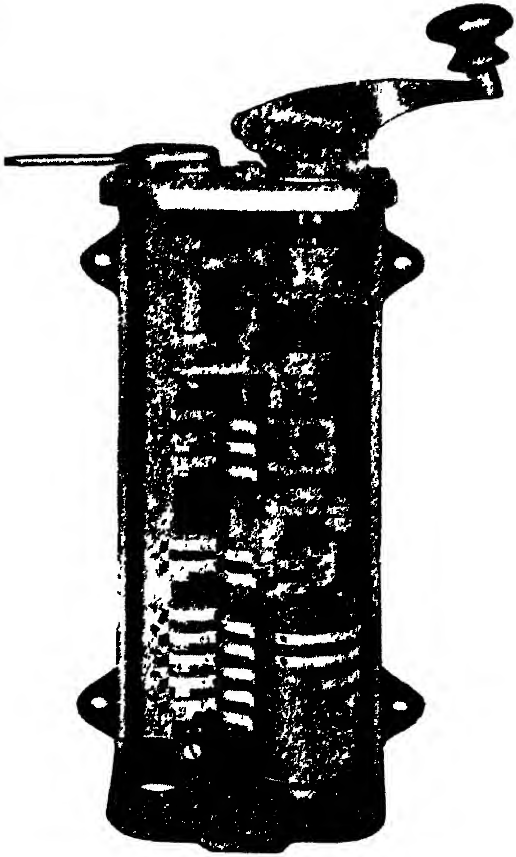


Fig 31.—Master Controller (Metropolitan Vickers).

The No-Volt Relay (or Low Voltage Relay). Owing to the opening of a circuit breaker in a sub-station, or from some other cause, it may happen that power is cut off from the line and restored again after a certain interval. If this should happen while a train is running at full speed and power remain off while the train is coasting to rest or to a slow speed, the sudden restoration of voltage to the line would produce a severe jerk to the motors, with a probable flash over. To prevent

this happening a no-volt relay is often fitted, consisting of a solenoid coil of fine wire bridged across the control circuit Its plunger is normally held up, against the pressure of a spring, and the loss of voltage on the line allows it to fall. Its connection is such that the relay coil can only be energised and the plunger raised in the "off" position of the controller, thereby ensuring that the driver's handle be put to the off position before the train can again start up To guard against unnecessarily interrupting the control in case of momentary loss of voltage, as may happen when the train passes over a set of points or crossings or a dead section, a dash-pot is fitted to allow the plunger to remain up for two or three seconds. If, therefore, voltage is restored within this time, a slight jerk to the train motors is all that will result and there will be no re-notching up to be done

The Control Governor. The control governor is another safety relay. Its function is to keep the control circuit of the train interrupted until there is a sufficient air pressure in the brake pipe to operate the brakes Without this governor a train may be started up by a motor-man who has omitted to close the compressor switch, so that there will be no brake power available when he wishes to stop. The control governor is not quite universally fitted, but it most certainly ought to be. It is fitted to the "train" or "brake" pipe of the Westinghouse brake, and is usually set to close as soon as the pressure rises to 50 lbs. per sq. in.

The Reverser. The Reverser in multiple unit controls is usually in the form of a rocking arm carrying the contacts and making electrical connection with suitable fingers for reversing the direction of motion of a group of two motors. This arm is rocked by an electromagnet or pneumatic cylinder operated from the master controller. In electromagnetic control systems two coils are required, one for forward and one for reverse rotation. No blow-out or arcing chamber is provided for the reverser, since it is always thrown over when the main power is off and therefore never breaks current. For very large motors, and particularly in locomotive work, this type of reverser is not used, an arrangement of contactors being used instead

The reverser, or contactor arrangement, is always interlocked with the circuit breaker for two reasons.—

(i) to prevent it from being reversed unless the main power is shut off, and

(ii) to ensure that the circuit breaker cannot close if for any reason a reverser should jam or fail to throw.

This prevents the two bogie trucks of a motor coach from pulling against each other in the case of failure of a reverser to throw, and allows the train to run with the circuit breaker cut out of such group

The Circuit Breaker. The circuit breaker, or line breaker, is a switch carrying the main power current for each coach and is arranged so that it can be set or tripped electrically from the driver's compartment It must also be automatic in action, i.e. capable of interrupting the circuit on overload, and will therefore be fitted with an overload coil carrying the main motor current of its group The circuit breaker is often a switch which, when set electrically, is held in position mechanically by means of a catch, being tripped either automatically on overload or by the trip coil. In such cases a special "set and trip" switch is provided in each driver's compartment by means of which all the circuit breakers, or line breakers as they are often called, on the train can be operated simultaneously.

In other systems one of the main contactors is used as an overload circuit breaker, being held in, electromagnetically and not mechanically, in conjunction with a separate overload relay which on tripping opens the energising circuits of the contactors. The driver's trip switch is unnecessary in this system, since the circuit breakers can be opened by switching off the control circuit.

In all cases, the breakers are arranged so that they can be "set" only in the off position of the controller, but can be tripped in any position A moment's consideration will show the need for this

Circuit breakers must be liberally designed both as regards strength and capacity to break large power currents. Their insulation must be suitable for the line voltage ; a magnetic blow-out is usually provided and separate arcing tips to take the burning effect of the arc. As the breaker closes the auxiliary or arcing contacts usually close appreciably before the main contacts, and for the same reason the main contacts break before arcing begins, thus protecting the main contacts from damage by burning. A wiping action is given to the contacts to rub off any roughness caused by arcing and thus ensure the contacts remaining smooth. The breaker must be well enclosed with asbestos millboard or other fireproof material, since in the event of a sudden earth or short circuit on the motors, the circuit breaker is called upon to interrupt a current far greater than the maximum current for which the overload trip can be set.

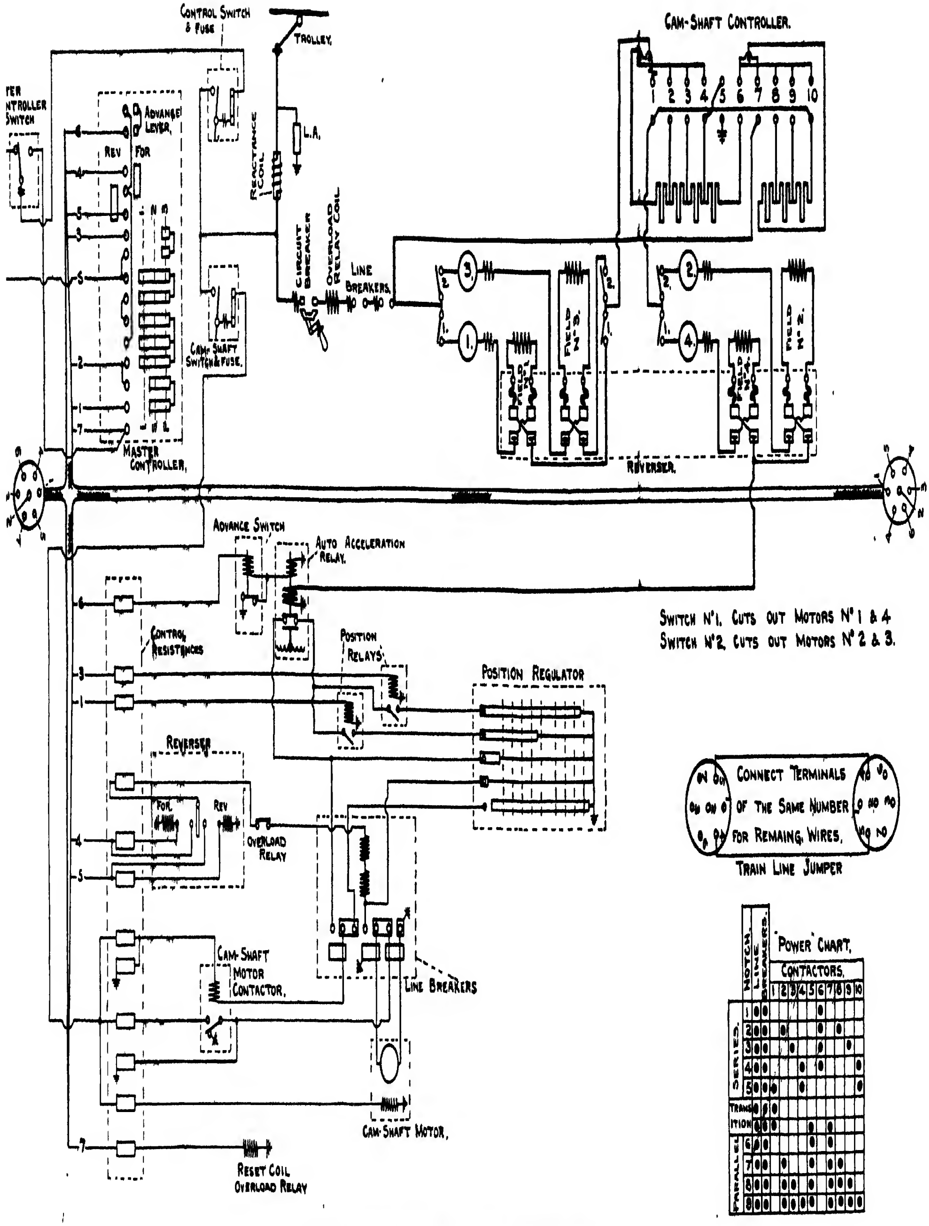


FIG. 41.—Control Circuit Diagram. All-Electric Cam-Shaft System.

Main Rheostats. Traction rheostats for multiple unit trains are now always of the cast-iron grid pattern, cast from a somewhat special grade of cast iron giving a low temperature coefficient of resistance and mechanical flexibility. The grids are assembled together upon rods covered with mica insulation and a series connection of the grids is obtained by inserting thin mica washers between alternate grids A rust-preventing paint is sometimes used. A broken grid can readily be removed and replaced by slackening the nuts on the supporting rods. Good ventilation of the grids is necessary and they are often bolted to the underframe of the coach. As the rheostats are expected to carry current only at starting they may be rated much higher, i.e. work at a higher current density, than would be possible for rheostats carrying current continuously; further, the early sections of the rheostats which are cut out first can be rated higher than the late sections which carry current throughout the starting period A number of these resistance grids can be seen in Fig 35.

In locomotive work the starting acceleration will probably be low and the current accordingly be on the rheostats for a much longer period than for multiple unit trains, while for shunting and goods locomotives the number of starts and stops may be great, and it may be desired to run for some time on any given controller notch. For these reasons the rheostats are usually designed to be capable of carrying the full starting current almost continuously. Since direct current locomotives often require to carry ballast to provide them with sufficient adhesive weight, there is no objection to large and heavy rheostats on the score of weight, and the cost of cast-iron grids is naturally small

Other Control Details.

Bus-line and Jumpers. In multiple unit trains a bus-line is often though not always run throughout the train In systems which use collector shoes and a third or fourth rail there are gaps in the conductor rails which cause the shoes to lose contact in turn, and a bus-line is very advantageous in allowing the power to the whole train to be picked up by such shoes as remain in contact. To carry the current from car to car, flexible "jumpers" are used. The use of such bus-line prevents the jerk which must occur at such rail gaps, while for overhead systems no gaps occur and a bus-line is not required. Jumper cables are required of course to carry the control, heating,

lighting and whatever other circuits are desired to be carried throughout the train Fig. 32 illustrates a typical 7-point control line jumper, the socket with the hinged cover being of course fixed to the car while the head or plug carries the flexible cable

Fuses. Main fuses are generally used to supplement the circuit breaker and are placed in the positive and negative sides of the motor circuit On cars using an overhead conductor, a main fuse is usually provided on the roof between the pantograph and the main cable, while in third rail systems a fuse is usually placed on the shoe beam above each collector shoe. In this latter case each fuse must be capable of carrying the full current of the train, momentarily when crossing a gap or continuously

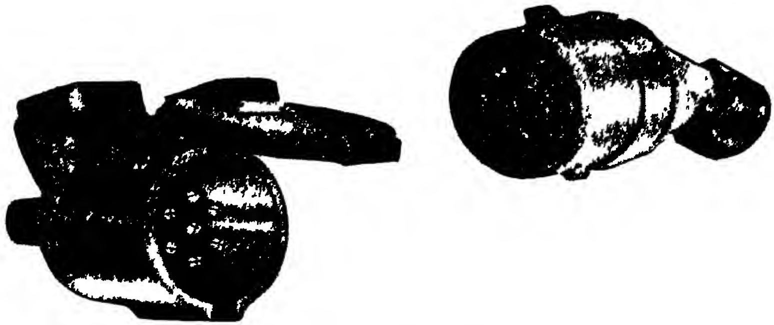


FIG. 32—7-point Jumper Head (B.T H).

when other shoes are knocked off or are packed up by a collection of snow, a condition which often obtains in winter. Since normally all these fuses are connected in parallel, the short-circuit current which would cause all of them to blow would need to be enormous and would certainly open the sub-station circuit breakers first, and the utility of providing such fuses is not very evident.

A main fuse usually consists of a copper strip with a hole punched in the middle to locate the point of fusion, the strip being carried in contact blocks with screw wedge contacts. The fuse is best enclosed in a well-made box of oak, dovetailed, with a hinged lid to facilitate easy renewal of the fuse and with sheet steel outside so arranged as to form a closed iron circuit which acts as an effective magnetic blow-out Such fuses must be so placed that there is no possibility of the arc

formed on blowing being able to reach any earthed metallic part, for the blowing of a fuse of such capacity represents an explosion of some violence and the air draught created by the train is capable of drawing out an arc to a quite unexpected length.

An example of each type of control system will now be described.

The Electro-magnetic Contactor System

The contactor switches are usually designed to close with a wiping motion of the contact tips in order to secure good contact between them and to rub off any roughness caused by arcing. The contacts normally fall apart by gravity, sometimes reinforced by a spring, which helps to promote a rapid breaking action. If the contactor is intended to break current, the arc is usually broken in a chamber of fireproof material, and in some modern designs separate renewable arcing tips are provided, a powerful magnetic blow-out being provided in series with the main contacts.

The principles of an electric contactor system will be best understood by studying one such type in detail, and for this purpose the system supplied by Messrs Oerlikon Ltd (Swiss), for the L. & N.W.R trains running on the Euston–Watford and North London routes, has been selected. This system is in many ways unique and less typical of general practice than the G E.–B.T H. system which is in general use on the London Underground Railway and in America, or the Westinghouse system on the L & S.W R., but it has the merit of extreme simplicity owing to the fewness of its interlocks and can be readily understood from the diagram even by those who have not previously studied electric train controls.

In an L. & N.W.R motor coach, there are two entirely separate electrical circuits, the Power circuit and the Control circuit, both operating on 600 volts direct current. The Power circuit comprises the motors, starting rheostats and such switches, etc., as carry the main driving current to such motors, amounting to some hundred of amperes. The Control circuit is traversed by a current of a few amperes only whose function is to excite the magnet windings of the contactors, switches and relays which control the main power current. The plate, Fig 34, shows the Control circuit only, in diagram form, and the functions of the various parts will be best understood by following them individually on the diagram. Fig. 33 shows the corresponding power circuit diagram.

On entering the driving cab of the motor coach, the motor-man closes the main switch and the two power switches for the motor groups He then closes the compressor switches, thus starting the compressor. The control switch is then closed, also the trip-cock switch. The removable key is then inserted in the reverse barrel shown on the left of the controller. The driver then depresses the Dead Man's Switch with his right hand, which must remain on the controller handle throughout all driving operations, and pushes the reverser key to the position marked "forward." The plunger of the no-volt relay is then heard to come up. With his left hand he moves the circuit breaker switch to the "on" position and holds it there a moment while the reversers throw to their forward position and the circuit breakers set The handle having been released, this circuit breaker switch springs back to the middle or neutral position as shown on the diagram.

As is seen from the diagram, the current flows from the positive side of the control switch, through the trip-cock switch to the finger marked + in the reverse barrel of the controller. On setting this barrel to the forward position, current flows to finger *m*, to the three fingers *f*, *q* and *n* at the top of the controller. These three fingers are all joined together electrically on the "off" position of the controller. Current accordingly flows from + to *n*, through the energising coil of the *No Volt Relay* and its resistance to wire 14 which is the general common negative return. The No Volt Relay becomes energised and lifts its plunger, thereby bridging the interlock contacts shown just above it on the diagram. There is now another path for the current to the No Volt Relay coil, viz through the *Dead Man's Switch* previously depressed, which allows a current from *f* through m_2 on the Dead Man's Switch, across the interlock contacts, energising coil, wire 14 to negative. At the same time a connection is made to finger *n* on the controller which carries the control current for the contactors When, therefore, the controller handle is moved round from the "off" position and the connection between *f*, *q* and *n* is broken, the No Volt Relay is supplied with current through the Dead Man's Switch. If the line voltage be cut off from any cause for a period long enough for the dash-pot of the No Volt Relay to allow its plunger to fall and open the interlock contacts, all control current will be interrupted and the contactors fall out, and current cannot be restored until the controller is brought to the "off" position, bridging *f* and *n* and again energising the No Volt Relay In addition to thus cut-

ting off all power to the train the opening of the Dead Man's Switch has the effect of applying the brakes by the following means

Current flows to *m′* of the switch through the *Brake Relay* to negative, energising its coil and lifting its plunger which allows air to escape from a pilot valve, releasing the pressure on the top of the emergency valve, which at once lifts and allows air from the train pipe to exhaust to atmosphere, thus applying the brakes with full emergency power. This electric operation of the emergency valve is bad practice, in the opinion of the writer, since if the Dead Man's Handle should happen to be released at a moment when power was cut off from the line, e g by the opening of the sub-station circuit breaker, the brakes would not be applied In most control systems the pilot valve is operated mechanically and this risk is thereby avoided

The Circuit Breaker Switch is now moved to the "set" or "on" position and held for a moment. Current flows from finger *q* in the controller, to *q*, and *a* in the switch to *a* in the reverse barrel. This barrel is set to forward and current passes to finger 3 and along wire 3 of the 15-core control cable throughout the train In each control group it passes through fuse 3, through the multiple cut-out switch, forward coil of the reverser to the throw-over switch (T O) and blow-out coil, to wire 14, which is negative. The forward coil is therefore energised and pulls the rocker arm of the *Reverser* over to *Forward*, which then mechanically throws the throw-over switch to the position shown in the diagram. The current no longer flows straight to wire 14 but passes through the interlock contacts on the rocker arm to 3*a*, through a section of resistance and thence through the *Set Coil* (S) of the *Circuit Breaker* to the common negative wire 14 The circuit breaker is then set Since the feed to the set switch is from finger *q* which is only live in the "off" position of the controller, it follows that the circuit breaker can only be set when the controller is shut off. It will be noticed that the circuit breaker could not be set until the reverser was completely thrown over ; so that if the reverser fails to throw for any cause the circuit breaker cannot be set and the pair of motors of the group remain inoperative.

Circuit Breaker Trip. On setting the circuit breaker switch to the "off" or "trip" position current flows direct from the positive control fuse to wire 2, through a small resistance to 2*a* and through the trip coil of the circuit breaker to negative. Since the feed to the switch does not depend on the position of the controller handle, it is evident that the circuit breakers can

be tripped at any time, a most necessary condition. Should the guard wish to shut off power from any other driving compartment he has only to close the control switch in that compartment and then put the circuit breaker switch to "trip," which will open all the circuit breakers on the train

It will be noticed that there is another tripping circuit from the trip switch through 31 on the reverse barrel to wire 2 and so to the trip coil. This connection is made momentarily whenever the reverser handle is moved from forward to reverse or vice-versa, to ensure that the circuit breakers are tripped (*a*) when the driver shuts down and leaves the controller and also (*b*) when testing out the operation of the controller when it is not desired to move the train In this latter case the driver should trip his circuit breakers, but this auxiliary contact is provided to do it for him if he should forget.

Before passing on to the contactor circuits, it may be necessary to explain two points about this particular form of controller which are somewhat unique. Firstly, when the controller is shut off, the whole of the interruptions of current take place at a *Central Blow-Out* whose terminals are *t* and *p* on diagram (shown to the right of 7, 9 and 11 fingers). This blow-out switch consists of two star-wheels driven by bevel gearing from the controller drum and is arranged so that the circuits break at *p* and *t* alternately on shutting off the controller, both being fitted with strong magnetic blow-outs and enclosed in asbestos or "uacolite" chambers As a result there is no arcing at the controller fingers, no blow-out to be provided and very little cost for maintenance. Secondly, the automatic operation of the control is obtained not by the alternate operations of the current relay coils as in the type "M," Westinghouse and other systems, but by means of a solenoid called the "*Clutch Magnet*" whose plunger in moving upwards drives through bevel gearing the main barrel of the controller. This barrel is mounted on ball bearings, and, when the controller is set for automatic operation, is mechanically free from the controller handle. Thus the motor-man normally brings his handle with a sweep straight round to full parallel, while the barrel follows point by point as driven by the clutch magnet, which in turn is controlled by the current limit relay. In case of failure of this automatic system, a knob on top of the controller can be lifted over from automatic to non-automatic, thus letting in a clutch and coupling the barrel with the controller handle so that the controller can be rotated manually. These features are the cause of the very

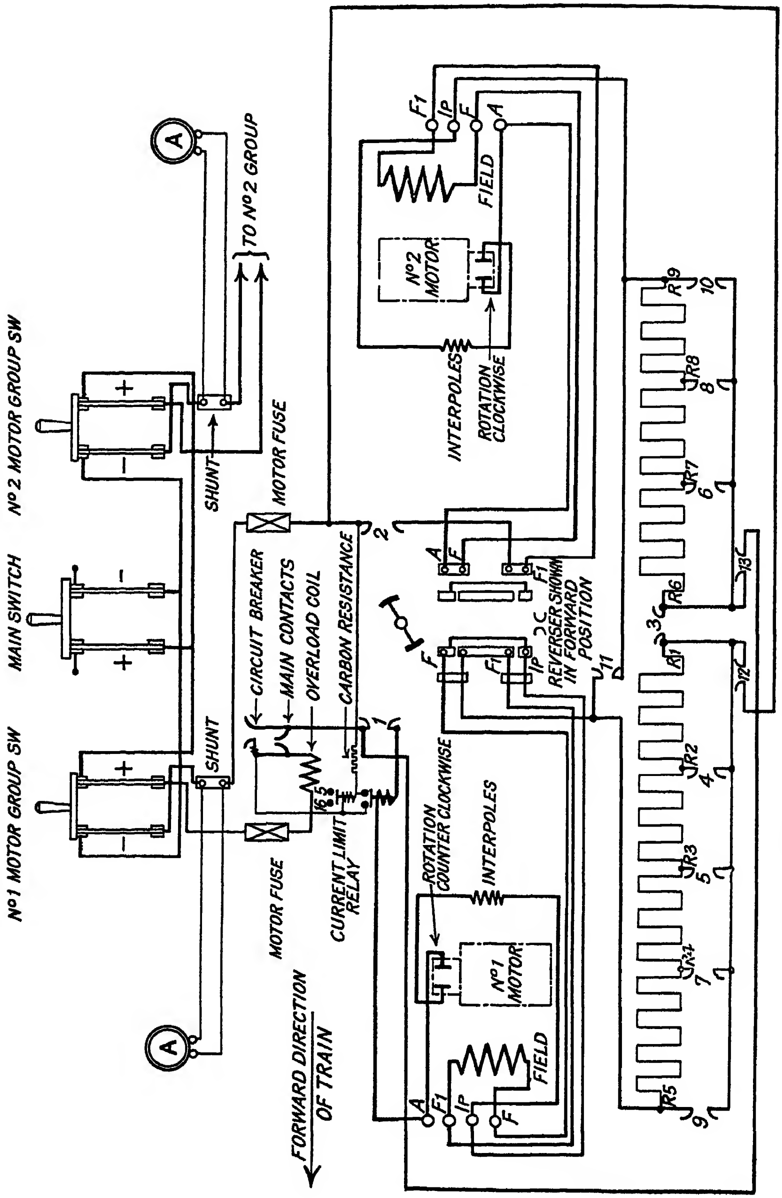


FIG. 33.—Power Circuit Diagram Electro-magnetic Contactor System

large size of the controller compared with that of the type M and other systems.

The clutch magnet circuit is as follows :—

From positive to finger O, finger *d*, through barrel to *e*, through barrel to *g*, interlock contacts and coil of clutch magnet to wire 5 of control cable. Through resistance to 5 and 16 contacts of the limit (i e current limit relay) of group 1, across through the limit of group 2 back through wire 5, through the last multiple cut-out switch contacts to negative wire 14 Through this circuit current flows and energises the clutch magnet which by gearing pulls the controller barrel round one point At the top of the plunger stroke the interlock contacts of the clutch magnet are broken and close again slowly with a dash-pot ready for the next stroke The dash-pot is fitted to steady the operation of the controller when testing its working with the train stationary. When the train is running, the limit contacts 5 and 16 are made and broken by the action of the main current, as explained previously, and it will be noticed that the two limit relays have their interlock contacts in series so that if there is any difference between them the closing depends on the limit which has the lower setting If one group has to be isolated, the multiple cut-out switch opens all contactor circuits but short circuits its 5 and 16 wires. This is necessary owing to the series working of these two limits. It will be noted that wire 5 in the control cable is not connected to its terminal in the connection box, so that the limits on the rear motor coaches are not operative, the speed of the train depending on the limits of the front motor car only.

Contactors. It will be seen that the middle part of the controller drum is divided into two parts insulated from each other. On the *first point* of the controller, finger *p* makes contact with 6 and the circuit is : (positive) *p* to 6, wire 6 in control cable, No. 6 fuse in each group, multiple cut-out switch, control resistance 8*r*, wire 6*a*, contactor coils 3, 2 and 1, wire 15, multiple cut-out switch, negative pole switch in controller, wire 14 (negative) The negative pole switch carries contactor coil current only and is a spring switch held closed in all open positions of the controller and opened only when the controller is closed It is clearly an additional safeguard to provide a double-pole break of the control current

Contactors 3, 2 and 1 accordingly close, which has the effect (as seen by reference to the motor circuit diagram, Fig. 33) of putting each pair of motors in series with all resistance in circuit.

The *second point* of the controller puts *t* and 7 fingers in contact, and the circuit continues through 7 wire, 7 fuse, multiple cut-out switch, control resistance 6*r*, wire 7*a*, interlock of 11 contactor, contactor 4, wire 4, R to 6*b* in the series-parallel relay, resistance *p*, wire 6*a*, contactors 3, 2 and 1 as before Thus 4 contactor is energised and a rheostat step cut out of the motor circuit The resistance of 6*r* and *p* is less than the 8*r* of the first point by exactly the resistance of one contactor coil, for since there are now four contactors in series instead of 3, a small section of resistance has had to be cut out in order to keep the current through the contactors uniform

The *third point* of the controller makes contact from *p* to 8, wire 8, multiple cut-out, 4*r* resistance, wire 8*a*, contactors 6 and 5, wire 7*a*, series parallel relay and contactors 4, 3, 2, 1 as before. Contactors 6 and 5 are thus energised

The *fourth point* brings *t* and 9 in contact, wire 9, multiple cut-out, 2*r* resistance, contactors 8 and 7, following on to 6 and 5 and back as before. Contactors 8 and 7 are thus energised

The *fifth point* gives full series; *p* to 10, multiple cut-out, wire 10*a*, contacts 10, 9, 8, 7, etc The contactors now energised are 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10, which arrangement corresponds to full series position of the motors, all rheostats being cut-out

The a point. This is a transition point. It brings up contactor 11, short circuiting all rheostats, and at the same time de-energises all resistance contactors, leaving 1, 2 and 11 only. Reference to the power circuit diagram will show that this does not affect the motor current at all, amounting merely to the opening of short-circuited contactors. The circuit is *t* to 11, multiple cut-out, 8*r* resistance, 11*a* wire, back interlock of 12 contactor, i e *t* to *f*, contactors 11, 2 and 1 to negative

The b point This is the bridge transition point and is worthy of attention. Contactors 12 and 13, the paralleling contactors, have to be energised and immediately they close 11 is to be allowed to fall out. The circuit is: *p* to 12, multiple cut-out, 6*r* resistance, wire 12*a*, contactors 12 and 13, back interlock of 12 contactor, i.e *t* to *f*, contactor 11 and back as in point *a*. As soon as 12 contactor closes, the front interlock is made and the back interlock broken. On the same point, however, fingers *n* and 13 on the controller have been brought into contact, sending a current through the operating coil of the series parallel relay and pulling it over from the series position to the parallel. This relay is energised at the same time as 12 and 13 contactors are energised and at the breaking of the *t* and *f* contacts there

is another circuit ready, viz, 11*a* to 53 on the series-parallel relay, from whence the circuit is made to contactors 2 and 1. When the *t* and *f* contacts open, the circuit through 11 contactor is broken and 11 drops out. The closing of the front interlocks of 12 contactor, 11*a* and 5*b*, has the effect of short circuiting No 3, the series contactor, thus ensuring that No 3 will be out while No 12 is in. The series-parallel relay is a device special to this system, for preventing the series and parallel contactors from coming in together. It is normally in the series and is pulled into the parallel position on the *b* point of the controller The motors are now in parallel, each with a section of resistance in series

The sixth point The circuit now is *t* to 7, fuse 7, multiple cut-out, 6*r* resistance, wire 7*a*, interlock of 11, contactor 4, R to 12*a* on the series-parallel relay, contactors 12 and 13 and back as before Thus No 4 contactor has been energised.

The *seventh, eighth* and *ninth points* are a repetition of the third, fourth and fifth in so much as they energise the same circuits to cut out rheostatic contactors until on the ninth point each motor is connected straight across the supply without resistance, which condition corresponds to full parallel.

The control diagram shows a 3-coach train unit, i e. motor car, trailer and driving trailer, the controller, control switches and relays being repeated in the driving compartment of the driving trailer It will be noticed that wires 3 and 4 are crossed over in the jumper cables and connection boxes. The crossing and re-crossing is necessary to allow of the trailer being turned round end for end at any time, the net effect being the cross over of 3 and 4 from the motor to the driving trailer, which is necessary because the forward position of the motor car is the reverse position of the driving trailer and vice versa. Wires 3 and 4 represent the forward and reverse coils of the reverser respectively, from the point of view of the motor car. The apparatus is shown in position in Fig. 35.

It will be evident that this control system differs from most of the well-known electro-magnetic contactor systems in the form of its automatic working and the extreme fewness of interlocks it requires. The only interlocks are those on 11 and 12 contactors and a mechanical interlock, in the form of a rocking arm, between 3 and 13 which are actually placed next to each other though shown separated for clearness in the diagram.

On 600-volt systems in which the full line voltage is used to energise the contactor coils, it is inconvenient to wind coils

for the full voltage and series resistances are generally used. When a system employs a direct current of about 600 volts it is natural to use the line voltage to supply the control circuit, 800 volts begin the maximum that has yet been used On

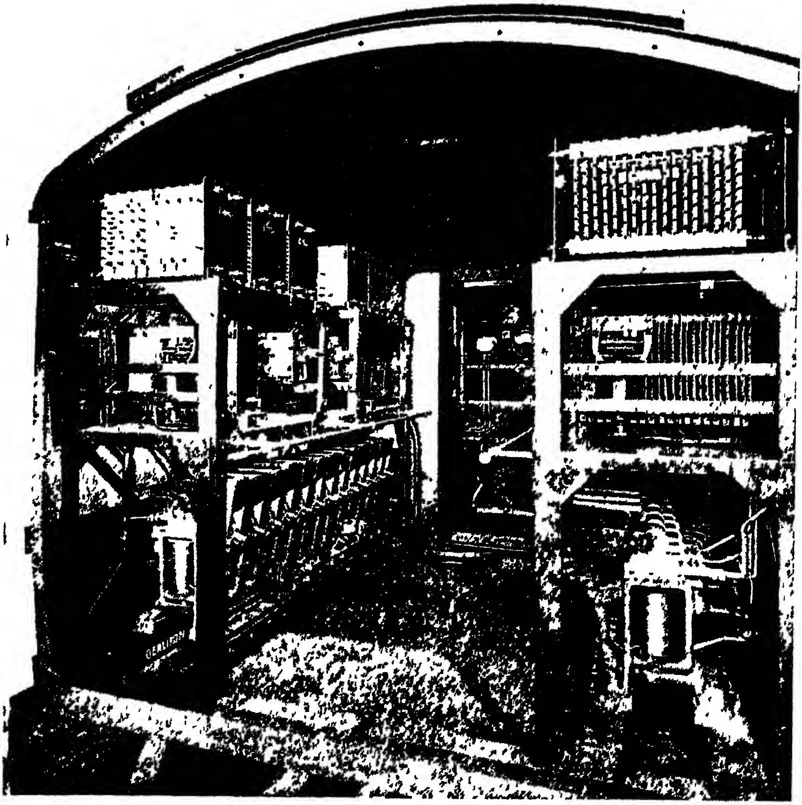


FIG 35.—Interior of Apparatus Compartment, L.N.W R.

1,200, 1,500 volts and higher pressure systems, it is usual to employ a dynamotor or a motor-generator to produce a more suitable voltage for the control. There is no reason in such cases for using a high pressure, arcing and burning of contacts are reduced and practice appears to be standardising on 32 volts.

The Electro-pneumatic Unit Switch System

In this system individual contactors are employed which are energised by compressed air cylinders controlled by electrically operated valves The solenoids of these valves are connected by multi-core cables to a master controller in the driver's cab Thus the actual control is electrical, while the energy for closing the contactors is pneumatic The compressed air cylinder, contactor and operating valve form one unit, self-contained and readily removable, which explains the designation "Unit Switch" usually applied to this system. A number of unit switches are grouped together as required The advantages of electro-pneumatic control are several, of which the following may be named.—

(1) The control voltage may be low, thus protecting the driver from the necessity of handling high voltage switches, which however well protected contain an element of danger.

(2) A compressed air cylinder is one of the lightest, smallest and cheapest ways of producing a high mechanical pressure In a unit switch of small dimensions a contact pressure of 115 lbs is easily obtained and a powerful spring of about 75 lbs. is available for opening the contacts instead of relying on gravity for this purpose

(3) The contact pressure is independent of line voltage, thus avoiding the tendency, which is found on electro-magnetic contactors fed from main pressure, of vibration and welding-up of contacts when operating on a very low line voltage.

The control voltage has been installed as low as 14 volts (Mersey Railway) but, as noted above, 32-100 volts is more usual. Such low pressures are economical in maintenance, there being little arcing or wear on contacts of master controllers, etc., and a low energy consumption for the control system. The air is supplied by the brake compressor, and since the air consumption for the starting operation of one motor coach is only about 0·3 cubic ft. at 70 lbs. per sq. in, the control necessitates a very small increase in the size of the compressor.

The unit type control system is manufactured by the Westinghouse Co of America and the Metropolitan Vickers Co. in England.

The Metropolitan-Vickers control system will now be described in some detail, the particular arrangement being that ordered for the Sydney Electrification (Australia) A diagram of the control circuits is shown in Fig. 36.

Master Controller. The master controller is of the drum type with main and reversing handles, as shown in Fig. 31 The dead man's handle is embodied in the main handle which moves upwards on being released, and mechanically operates a drum switch which flies back into the " off " position and interrupts the control current, causing all line breakers and contactor switches to open. At the same time a small pilot air valve is opened which causes the emergency valve to be unseated and applies the brakes with emergency force After the handle has thus operated, the driver must bring it back to the " off " position before he can release his brakes and restart the train. The controller is fitted with three drums of bakēlite mounted on a common shaft, viz . reverse drum, cut-off drum and main control drum The reverse drum, to which the top three fingers make connection, is operated by the reverser handle and is mechanically interlocked with the operating handle so that the latter cannot be depressed and moved from the " off " position unless the reverser handle is in either the " forward " or " reverse " position. The reverser handle also acts as a locking key, since it cannot be removed from the controller nor from its " forward " or " reverse " position until the main handle is brought to the " off " position.

The cut-off drum has two contacts only, is connected in the control supply circuit and is always used to break the circuit, i.e. when the handle is brought back to the " off " position.

The main control drum with its five fingers is used to close the contactors in their proper sequence.

The controller is seen to be small and very simple and no magnetic blow-outs or arc shields are required.

The number of controller notches is four, viz :—

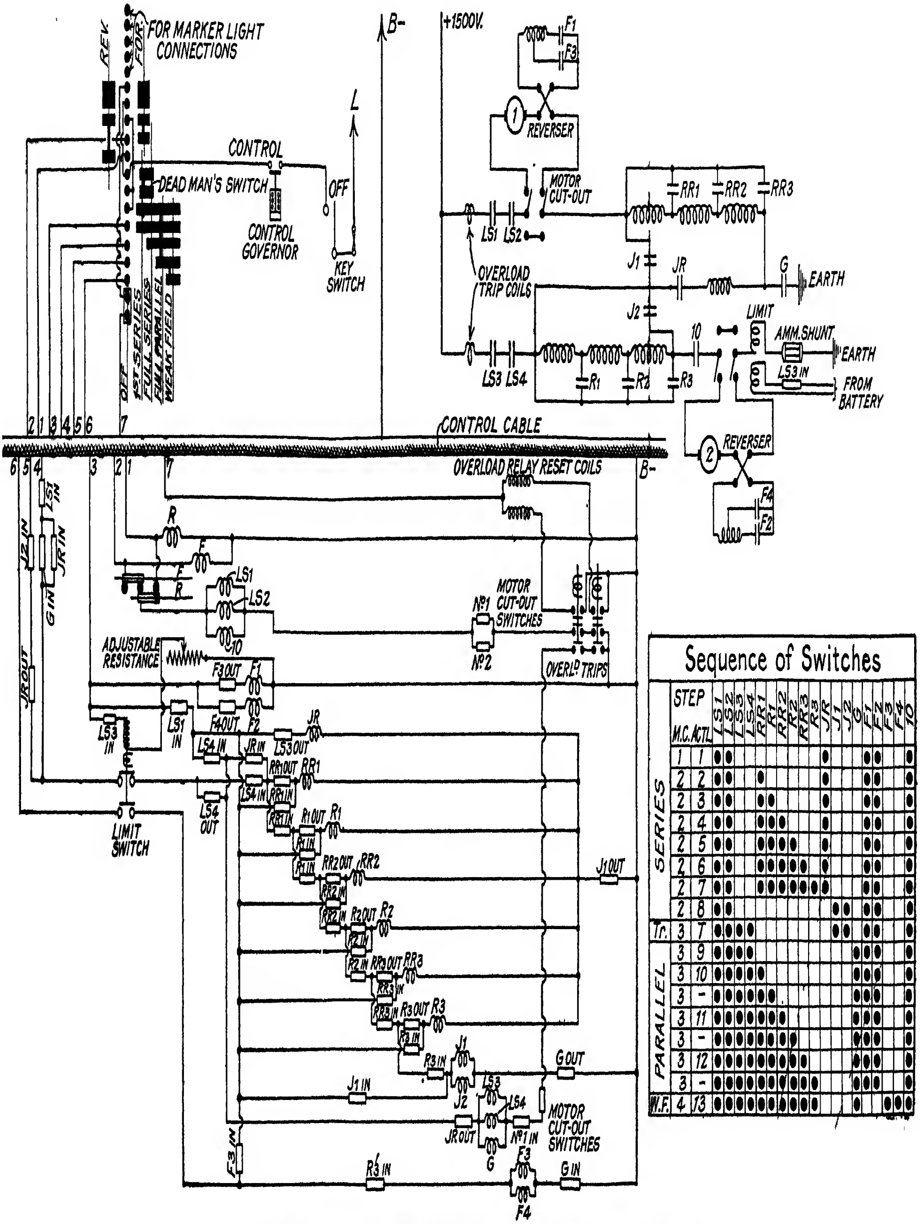
(1) Switching or shunting notch, with motors in series and all resistance in circuit ;

(2) full series ;

(3) full parallel ;

(4) weak field.

The control is so arranged that on bringing the handle to 2, 3 or 4 positions, the contactors come in automatically step by step under the control of the current limit relay until the full series, full parallel, or weak field positions are reached. The motor-man cannot notch up more rapidly than the current limit relay will allow, but if he desires to obtain a slower rate of acceleration the handle can be put to full series and immediately



Sequence of Switches

	STEP M.C.	STEP ACTL.	LS1	LS2	LS3	LS4	RR1	R1	RR2	R2	RR3	R3	JR	J1	J2	G	F1	F2	F3	F4	10
SERIES	1	1	●	●									●				●	●			●
	2	2	●	●			●						●				●	●			●
	2	3	●	●			●	●					●				●	●			●
	2	4	●	●			●	●	●				●				●	●			●
	2	5	●	●			●	●	●	●			●				●	●			●
	2	6	●	●			●	●	●	●	●		●				●	●			●
	2	7	●	●			●	●	●	●	●	●	●				●	●			●
	2	8	●	●										●	●		●	●			●
Tr.	3	7	●	●	●	●								●	●		●	●			●
PARALLEL	3	9	●	●	●	●										●	●	●			●
	3	10	●	●	●	●	●									●	●	●			●
	3	-	●	●	●	●	●	●								●	●	●			●
	3	11	●	●	●	●	●	●	●							●	●	●			●
	3	-	●	●	●	●	●	●	●	●						●	●	●			●
	3	12	●	●	●	●	●	●	●	●	●					●	●	●			●
	3	-	●	●	●	●	●	●	●	●	●	●				●	●	●			●
W.F.	4	13	●	●	●	●	●	●	●	●	●	●				●			●	●	●

FIG. 36.—Control and Main Power Circuit Diagram. Electro-pneumatic Unit Switch System.

returned to the first notch, and each time this operation is repeated a fresh step of resistance is cut out, always provided that the current has fallen low enough to allow the limit relay to operate On reaching full series, the same operation can be performed for the parallel notches. This feature is of use when the train is being started under difficult conditions, such as a severe gradient, slippery rails, or when shunting

Current Limit Relay. This relay is of simple design, the setting and adjustment being made by varying the position of an iron plunger by means of a milled-headed screw and spring.

The control interlock is a flat disc closing contact against light spring pressure, the ordinary vibration of the train being sufficient to cause it slowly to rotate and so maintain a clean contact surface

Contactors. The switch is operated by a piston provided with a cup leather packing and is moved by compressed air. As the piston moves it compresses a powerful spring, whose force is then available to open the switch when control current is shut off. Admission of air is controlled by a small valve operated by a solenoid (the coils of which take about 14 watts) and the valve stem is extended outside so that it can be depressed by the hand for testing purposes. The air connections between individual switches of a contactor group are made by means of a small pipe section, the broad cheeks at the ends of which allow of taking up small variations of distance. The switch element is built up on two vertical steel bars mounted on the cylinder casting and insulated with bakelite micarta, the various parts being clamped on the bars The switch contacts have a wiping action and are fitted with a powerful magnetic blow-out. The switch units are mounted in the group on two angle irons with one bolt in each, so that the work of disconnecting, removing or replacing a switch with its main, control and air connections is a simple matter. Interlocks are fitted at the back of the contactor and are operated direct by the movement of the piston. The interlock fingers are of spring steel mounted on an insulating base The Westinghouse Unit Switch is of very similar design.

Line Switches. The line switches are identical in construction with the contactor switches and take the place of a circuit breaker. Two line switches, LS1 and LS2, are arranged in series so that the normal making and breaking of the load is shared between them. When an overload occurs these line switches are made to open by means of the overload relay.

LS1 and LS2 carry the whole current while the motors are in series, and LS3 and LS4 come in to share the load when the motors pass to parallel, as shown in the main power circuit diagram, Fig. 36

Reverser. The reverser provides for the reversal of the motor fields and is mounted in a group with the line switches. The reverser is operated electro-pneumatically by two pistons working in cylinders and driving the drum through a rack and pinion. Electrically controlled valves of the same design as used on the contactor switches are used to control the air supply to the pistons Interlocking fingers are provided to ensure that the reverser is completely thrown into its proper working position before the main circuits can be closed

Overload Relay. This relay has a series operating coil in the main circuit exactly as in the case of the current limit relay, the effect of an overload being to break the control current to the line switches, causing them to open and so cut off all power to the motors. The overload relay can be reset by means of a reset coil which releases a latch which holds the relay up after it has been operated by an overload. The reset coil is energised by means of special " reset " contacts on the drum of the master controller, which make contact only in the " off " position of the controller, so that after the line breakers have opened on overload the controller must be brought to the " off " position before they can be closed again. The no-volt relay is no longer considered necessary, the overload relay being relied upon to take care of any overload resulting from re-applying current after a shut down.

The air supply is taken from the main reservoir of the brake system at about 100 lbs. per sq. in through a reducing valve which reduces it and maintains it at 70 lbs per sq. in

The control current, as also that required for car lighting, is obtained from a motor-generator of about 5 kw. rating. The motor is compound wound, the generator being plain shunt wound with an automatic voltage regulator to maintain constancy of voltage. The 1,500-volt switch for the motor-generator and the compressor motor are electro-magnetic unit switches all controlled from the 32-volt supply, so that there is no high voltage apparatus in the driver's compartment. A battery, charged off the motor-generator, is used for emergency lighting and control

The control circuit diagram which is shown in Fig. 36 is extremely simple to read, the only explanation needed being that

where an interlock is marked, for example, "J1 out," the significance is that this interlock is closed when contactor J1 is out. The sequence diagram shows the contactors in and out on each controller step.

A great number of equipments of the Unit Switch type are in existence and the system ranks among the best in use. The apparatus is manufactured for location either inside the car or underneath It will be noticed that the correct sequence of contactors is secured by means of interlocks. In some cases it has been considered safer to fit a special "sequence switch," consisting of a drum operated by an air engine of similar design to that used on the pneumatic cam-shaft control. The contacts on this drum ensure correct sequence, obviating the need for most of the interlocks at the back of the contactors The Westinghouse Co. prefer to use a sequence switch, while the Metropolitan Vickers Co. prefer the arrangement described.

The Pneumatic Cam-shaft Control System

The cam-shaft system was developed some years ago and represents an attempt to avoid complication and the large number of interlocks which are found necessary in the electro-magnetic contactor and the electro-pneumatic unit switch systems

The successive contactors are closed by a series of cams fixed to a shaft which is made to revolve by a small pneumatic engine controlled in its turn from the master controller, and the correct sequence of contactors is therefore ensured by positive mechanical means. The final control is thus electrical, the mechanical force used to close the contactors being obtained from compressed air, as is shown diagràmatically in Fig. 27.

This system, which has been developed by the General Electric Co of America and is also manufactured by the sister company, the British Thomson-Houston Co , has been successfully used by a number of railways, notably on the later stock of the London Electric Railways whose particular system has been selected for description.

Scheme of Operation. The master controller is of the usual type and controls the "on" and "off" valves of the air engine as shown in diagram form in Fig. 37 This pneumatic engine consists of a cylinder containing a double-ended balanced piston, which rotates the cam-shaft by means of a rack and pinion. Its motion is controlled by two valves known respectively as the "on" and "off" valve. In the "off" position

of the controller handle (position 1 of Fig 37), air pressure is applied to the " off " piston through the " off " magnet valve, while the " on " magnet valve allows any air in the " on " cylinder to pass through to atmosphere.

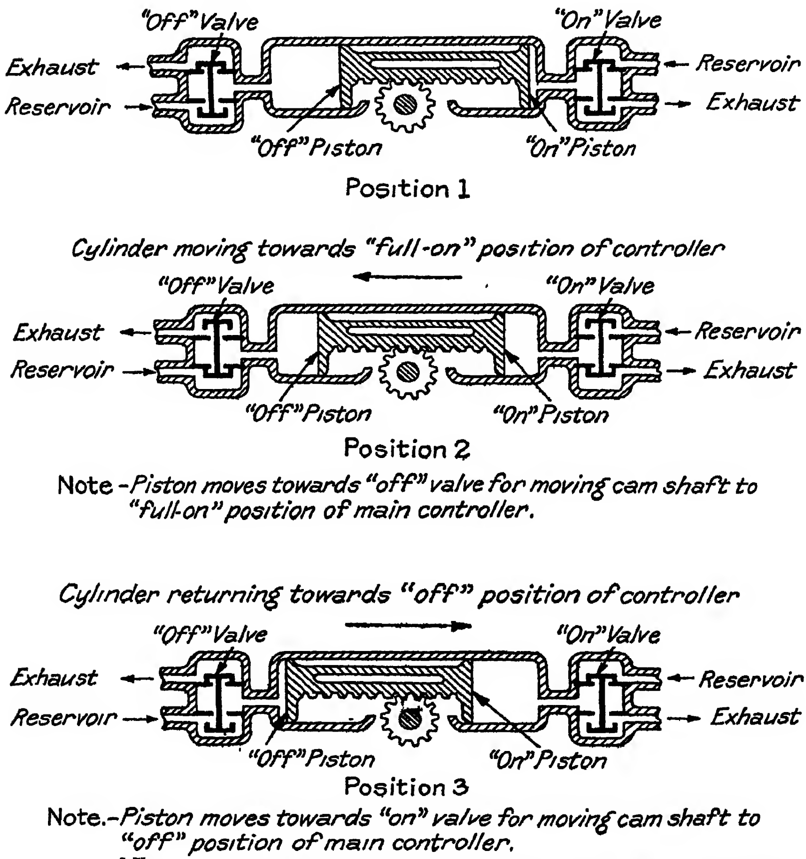


FIG. 37 —Diagram showing operation of " On " and " Off " Magnet Valves with relation to the Air Piston operating Cam-shaft.

When the master controller is switched on, the reverser throws, the line breaker closes and then both " on " and " off " magnet valves are energised and lifted. This applies air pressure to the " on " piston and allows air to escape from the " off " cylinder. The piston therefore moves towards the " off " valve,

rotating the pinion and cam-shaft by means of the rack and thereby closes the necessary contactors to allow the motors to receive current

The current limit relay then operates and de-energises the " off " valve which falls and cuts off air pressure to the " off " piston. The pressure on the two pistons (which as is seen are mechanically speaking the sides of the same piston) is now equalised and the movement of the piston ceases Subsequent controller points are obtained by alternately energising and de-energising the " off " magnet valve, the " on " valve remaining energised, thus allowing the rack and pinion to move the cam-shaft to the various positions corresponding to the master controller notches

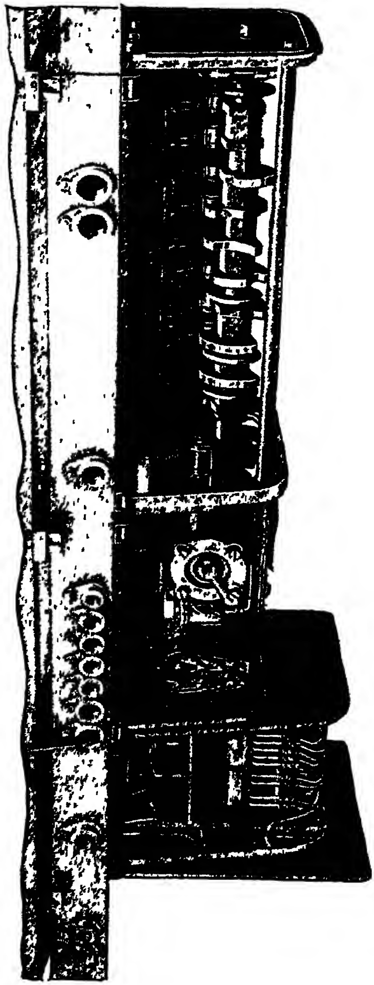


FIG. 38.—View of Main Motor Controller of Electro-pneumatic Control Equipment (covers removed), showing the Cam-shaft, Line Breaker Interlocks and one end of Air Cylinder.

If the master controller be now brought to the " off " position, both the " on " and " off " magnet valves are de-energised (see position 3, Fig. 37), and pressure is thus applied to the " off " piston and air released from the " on " cylinder, causing the rack to move towards the " on " magnet valve and so rotating the shaft, bringing the contactors back to the " off " position. A general view of the control system is shown in Fig. 38 and a typical contactor in Fig 40.

The line breaker and reverser are both operated by air pressure,

each having its own air cylinder and piston, whose operation is controlled by an individual magnet valve. A star-wheel and pawl is provided on the cam-shaft to bias the rotation of the shaft to definite positions. The air for operating this system of control is taken from the main brake reservoir, through at least 15 ft. of cooling pipe, which drains backward towards this reservoir, and through a horse-hair strainer to an auxiliary control reservoir, thence through an insulating joint to the several control cylinders. The pipes are galvanised, and require to be well pounded with a light hammer and all detachable scale blown out before being finally connected up.

The electric power supply for working the control is taken from the live contacts of the main switches, through a double pole control switch and a pair of fuses; thence the positive line passes through one way of a two-way switch to the controller, whilst the negative line passes directly to the controller. The other way of the two-way switch is for the purpose of energising a control wire, which runs through the train for setting the overload relays; thus in the act of setting these relays power is cut off from the controller circuits, opening the line breakers, releasing the valves of the main engine, and dropping the potential relay, which does not pick up again, even if power be re-applied to the control, until the cam-shaft has returned to its "off" position. The interlock contacts P_1, P_2, short-circuited in the "off" position of the control drum, are bridged also by a resistance of 2,800 ohms, which prevents the relay picking up, but suffices to hold it up when once closed

Function of Several Control Wires. There are nine wires in the control bundle. No 1 actuates the "off" valves on notches, through the contacts of the current limit relays. No. 2 actuates the "off" valves in transition between notches, through the lifting coils of the current limit relays, it also sets the negative line breakers and actuates the "on" valves. No. 3 controls the transition between series and parallel, Nos. 4 and 5 actuate the reversers and set the positive line breakers No. 6 actuates the current limit relays through the medium of the advance lever. No. 7 is for setting the over-load relays. No. 8 is a common return wire. No 10 is the connection to the negative shoe, and this wire is characteristic of the system with insulated return

Succession to Switching Point. In the "off" position of the cam-shaft, the contactors S and R6 are closed. In Fig. 39 the reverser is shown thrown for forward motion, if it were desired

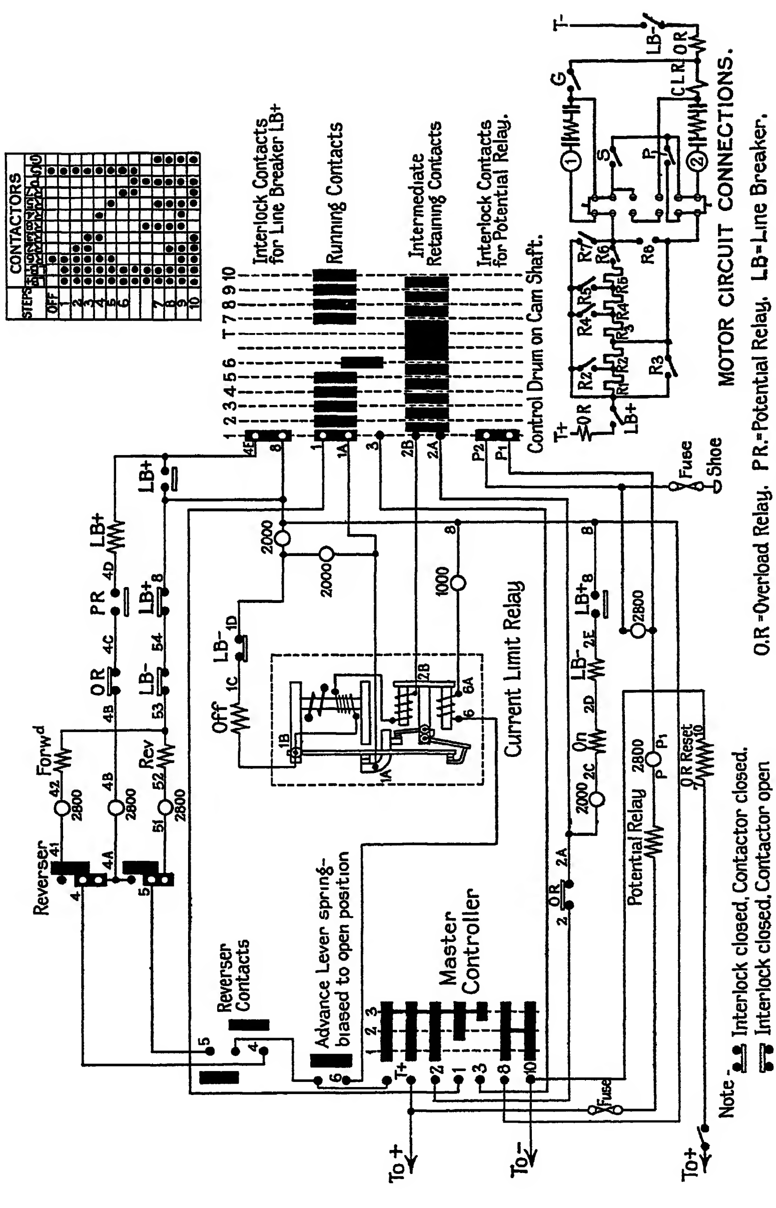


FIG. 39.—Simplified Connections for Pneumatic Cam Control.

to reverse, the necessary circuit would be made on the first control point from T through 5, 51, 52, 53, 54 and 8, provided that both line breakers are open. The coils marked "Forw^d" and "Rev." represent the actuating coils of the reversing magnet valves As shown for forward motion, however, a circuit is made on the first control point through 4, 4A, 4B, 4C, 4D, 4E and 8, which picks up the positive line breaker, provided that the overload and potential relays are both in, and that the control drum is in its "off" position The positive line breaker in closing makes another connection from 4E to 8, which maintains the circuit when the control drum has been rotated; it also completes a circuit from wire 2, through 2A, 2C, 2D, 2E and 8, which picks up the negative line breaker and actuates the "on" valve The main circuit is now complete, with motors and grid rheostats in series, and the motors start up

Succession to Running Points. On the second point the wire 1 is energised, actuating the "off" valve through 1A, 1B, 1C, 1D and 8, and causing the cam-shaft to rotate With the rotation of the control drum the circuit through 1 and 1A is opened, but the "off" valve is still actuated through the circuit 2, 2A, 2B, 1B, 1C, 1D and 8. This circuit, passing through the lifting coil of the current limit relay, breaks the contact between 1A and 1B which is held open, after the circuit through the lifting coil has been opened by the rotation of the drum, as long as the current in the series coil exceeds the value for which the relay has been set. Thus, a portion of the rheostat having been cut out by the closing of contactor R_2, the rotation pauses on the second notch until the motor current has decreased to its predetermined minimum, when rotation starts again and the action is repeated until the sixth notch is reached, at which stage rotation ceases. In passing to the third point of the controller the wire 3 is energised and takes the place of 1 in actuating the "off" valve, thus restarting the rotation of the cam-shaft; then, having passed through a transition period during which the connections shown in the figure are made successively, it takes the parallel notches in the same manner as the series notches were taken. The sequence in which contactors are closed or opened by the rotation of the cams is shown in the diagram at the top of Fig 39, the location of the contactors being shown in the motor circuit connections at the foot of this figure.

Acceleration. In case it is desired to accelerate the train notch by notch, at a rate faster or slower than the automatic

devices are set for, this can be done by means of the advance lever, by which the by-pass coil is energised through the wire 6. This actuates the "off" valve by completing the appropriate circuit through 1A, and the armatures of the hold and by-pass coils, to 1B, in transition from notch to notch this circuit is broken by the attraction of the holding coil armature, and the magnet is devised so that the by-pass coil retains this armature once it has been attracted by the holding coil Thus the action pauses on the next notch until the circuit through 6 is opened by the release of the advance lever, upon which it

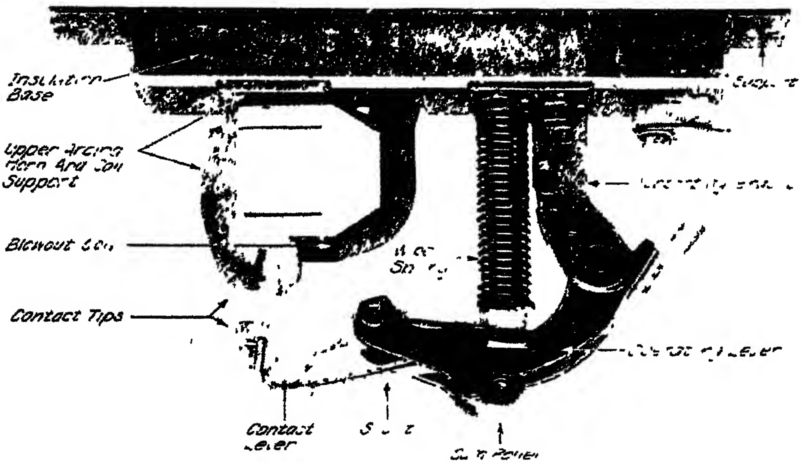


Fig. 40 —Cam-operated Contactor.

can be re-applied immediately The advance lever is used also in testing the control apparatus, as without any current in the motors the control can be notched up from point to point due to the fact that when the armature is closed the contacts are opened mechanically, preventing any further advance of the control whether main motor current is flowing or not.

All-Electric Cam-shaft Control System

This type of control, which is manufactured by the English Electric Co, is a fairly obvious development of the pneumatic cam-shaft system just described, since the cam-shaft is here rotated by electric motor instead of pneumatic engine.

The equipment consists essentially of .—

(*a*) A cam-shaft rotated by a small motor which is controlled by relays and by the master controller. The cams on the cam-shaft open and close the contacts in definite sequence by means of a " position regulator "

(*b*) Two cam-operated line breakers to break the main circuit

(*c*) Reverser, current limit relay and the usual operating gear

As in the air cam-shaft system, the cams entirely obviate the need for interlocks on the contactors and ensure correct sequence of contactors by mechanical means Since none of the contactors break the current except the one which deals with the current broken during transition from series to parallel, only this one requires to be fitted with a magnetic blow-out and the absence of blow-outs on the others allows of compactness of the contactor group

Line Breakers. Referring to Fig. 41, the line breakers are closed by means of cams on the first movement of the cam-shaft The further movement of the cam-shaft leaves them free to open, but they are held in position by toggles which are retained by solenoids, and until these solenoids are energised the rotation of the cams will not close the line breaker The breaking of the electrical circuit of the solenoid causes the line breaker to open, and this is effected either by the action of the overload relay or by the return movement of the master controller. It is to be noticed that a failure of line voltage will also cause the line breakers to open circuit. In such an event the restoration of line voltage will cause the cam-shaft to return to the " off " position, the line breakers will then close and the cam-shaft run up to its original position, there being thus no need for the driver to shut off and restart. An interlock is provided on the line breakers so that the cam-shaft cannot rotate in a forward direction until the line switches have closed, or backwards until they have opened. Hence the main circuit is always made and broken on the line switches alone. For operating the breakers on overload, a separate overload relay is provided which breaks the current in the line breaker holding coils and allows the breaker to open. The overload trip can be re-set from a switch in the driver's cab, but not until the cam-shaft has returned to the " off " position.

Reverser. The reverser is of the usual electric solenoid operated rocker arm type and calls for no detailed description.

Cam-shaft. The cams are of steel, mounted on a mica-insulated steel shaft. They are all alike but are set at different angles and each in turn closes a contactor against a spring

pressure which ensures a quick opening when the pressure is released. The contactors are shown in Fig 42

The position regulator is a drum type contact switch mounted on a shaft which is connected by a clutch to the cam-shaft.

Cam-shaft Motor. The cam-shaft is gear-driven by a small shunt-wound motor whose field is kept fully excited. The rotation is stopped at each position by short circuiting the armature under full field, producing a very positive and instantaneous stop. The short circuiting of this armature is done through the contact of the cam-shaft motor relay which closes when the coil is de-energised This relay is de-energised by the opening of contacts on the position regulator or the current limit relay The motor and cam-shaft are restarted when the traction motor current has fallen with increasing speed of the train sufficiently to allow the current limit relay to close again. The position regulator allows the cam-shaft to be rotated, step by step, under the control of the current limit relay, until its position corresponds to that of the master controller handle.

Master Controller. The master controller is provided with a main handle and a removable reversing handle mechanically interlocked with each other as usual, i.e. so that the controller handle is locked in the off position unless the reversing handle is set to either forward or reverse, also the reversing handle cannot be removed until the controller is set to the "off" position.

The master controller is small and contains a main drum making contact with fingers connected to the train control wires which carry current to the various position regulators. All the individual series and parallel notches are marked on the controller top and the handle can be used either manually or automatically according to the position of the reversing handle, which is fitted for automatic or manual operation in either direction.

General. Most of the advantages claimed for the pneumatic cam-shaft system apply equally to this all-electric cam system.

The equipment can be operated directly from the line on voltages up to 600 volts. Above this voltage a motor generator is usually supplied to reduce the control voltage to 100 or 120 volts, more often the latter. The English Electric Co prefer this pressure to a lower one on account of the interruption which can be so easily caused by a trifling amount of dirt on any of the contacts and the consequent need for a high standard of maintenance.

For voltages above 600 shunt transition is preferred by the English Electric Co to bridge transition for the main motors

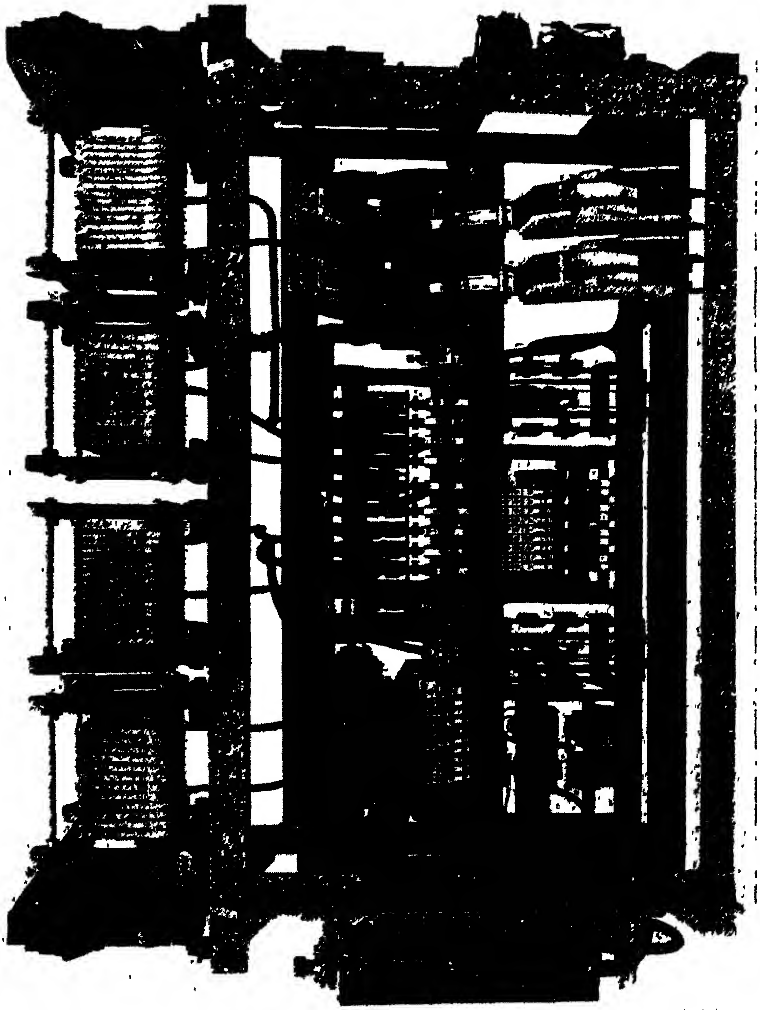


FIG. 42.—Electric Cam-shaft Control, Cab Type.

when passing from series to parallel. This form of transition is preferred in order to keep the field and interpole coils perman-

ently earthed even in transition so that the potential across them is always small, with correspondingly small risk of breakdown. The change necessitates fitting two of the contactors with arc chutes and blow-outs.

A large number of English Electric cam-shaft controls have been manufactured notably for locomotives and motor coaches for the Chemin de fer du Midi, France, for New Zealand, Spain, Japan, India, and Morocco. Fig. 42 gives a general view of the equipment arranged for mounting in the cab

The Earth Return on Trains. To the novice it often appears puzzling that so large a current as that used by the traction motors can be returned by means of a connection to the frame of the car or bogie, seeing that the final contact is made by the wheels, the only connection to which is through the bearings, all of which are well lubricated. In practice, the compressor, control, heating, lighting and other auxiliary circuits have their negative return bolted to the car underframe, while the negative of the motor circuit is connected to the bogie framework. The auxiliary circuit has to pass through the lubricated centres to the bolsters and so to the bogie, but the surfaces are large and the current small In the case of the motor circuits, if the figures for the 200 h.p. 1,200-volt motors of the L. & Y. Railway are taken,* the full-load current per motor is 155 amperes, which can pass to the wheels by way of the two suspension bearings, each $6\frac{1}{2}$ in. diam $\times$ 13 in. long, and the two axle bearings, each 5 in. diam. $\times$ 10 in long. The bearing surface of each will be the projected area, i.e. diameter $\times$ length, which totals 269 sq. inches for the four bearings, and the current density is therefore less than 0·6 amperes per square inch.

In this calculation no account has been taken of the conductivity of the motor bearings to the pinion and thence to the gear wheel, nor of the fact that there is a good mechanical connection through the buffers and draw-gear of all cars, so that the trailer wheels are also available for carrying current. There is in practice no difficulty whatever in passing current at such a low current density through lubricated surfaces, and no pitting is found in the bearings or journals.

* Hughes on Electrical and Mechanical Equipment of All-metal Cars of the L & Y. Railway. I.C.E, April 8, 1919.

CHAPTER V

RHEOSTAT CALCULATIONS

Calculation of Rheostat Steps. In starting up the motors of a direct current train using series-parallel control, it is usual to employ automatic acceleration by means of a current limit relay as described in Chapter IV. On the first controller notch the current rises to a certain value which falls gradually as the speed rises until it reaches the limit for which the relay is set, after which the relay operates and allows the current to rise to another peak value. This cycle of operations is repeated point by point until all resistance is cut out, the transition being then made and the notching repeated in parallel until full parallel is reached. For smoothness of starting it is naturally desirable to provide as many steps as possible and to arrange the current rises on each step uniformly; furthermore, it is usual for the sake of economy to utilise the same contactors and rheostats in parallel as in series. It is a comparatively easy matter to calculate a satisfactory set of rheostat values for the series part of the starting operation, but the values so chosen may not fit in so well in parallel and a measure of compromise may have to be adopted.

A comparison of the series and parallel curves of speed to a base of current shown in Fig. 43 shows that the slope of the parallel curves is sharper than in series, for which reason it is usual to provide one controller point less in parallel than in series

The problem of calculating the rheostat steps can be approached from several angles For example, it may be desired to design control gear to produce a certain starting acceleration. Calculating the tractive effort and therefore the current required, we may settle the limits between which the current is to be allowed to fluctuate and from this deduce the number of controller notches and the value of the corresponding resistance to each On the other hand the control system may be well standardised and the

number of controller notches definitely decided, so that the problem to be solved becomes one of calculating the most satisfactory

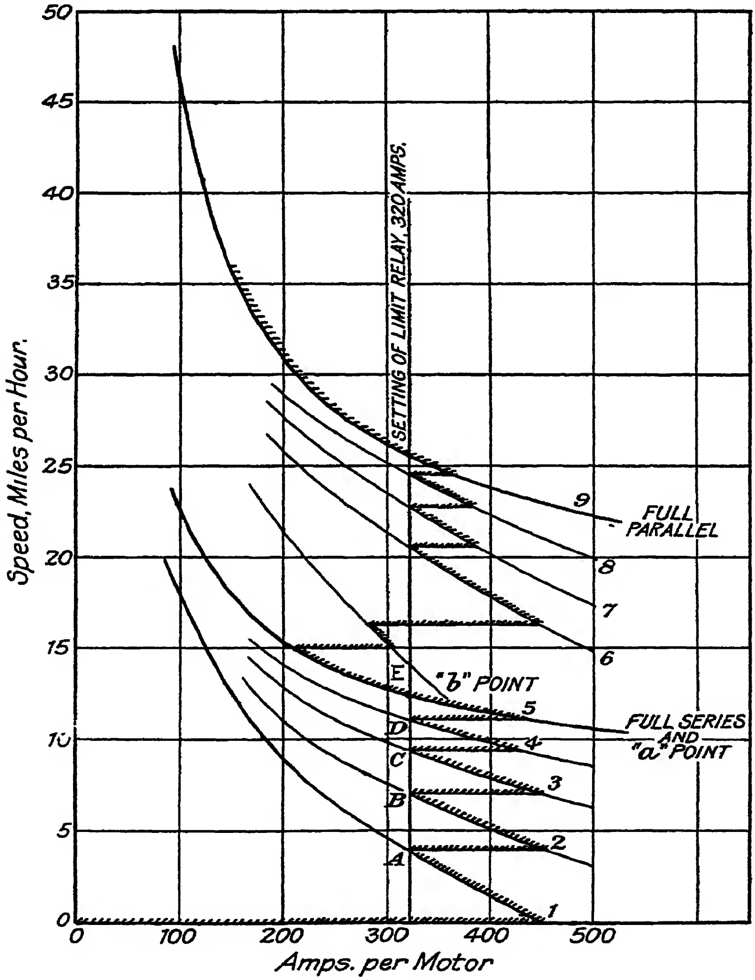


FIG. 43.—Controller Notching Curves.

rheostat steps to suit the control system In such a case we may desire to produce as high an acceleration as possible or we may desire to limit the current peaks for the sake of keeping down the

peak load on sub-stations or of avoiding slipping the wheels We may also desire the first notch to produce a low current peak and so allow the train to start gently, which will be a great convenience for shunting or "switching" operations

In any case, if the matter of the requisite rheostat steps be approached mathematically, a series of equations is arrived at which can only be solved by a process of trial and error. As such calculations are often tedious, various graphical methods have been devised for reducing the labour necessary, but such methods do not necessarily produce a definite number of steps. The method which is explained in this chapter has the merit of being derived from first principles, involving no approximations and permitting the actual current variation to be seen in curve form, which is particularly valuable when compromises and adjustments come to be made. It is also of interest to note that it is the method invariably used by the large manufacturing companies. The method will be best understood by working out an example and depends upon the rule that for any given current the actual speed is proportional to the back E M.F. or more precisely—for any given current .—

$$\frac{\text{speed at any applied voltage}}{\text{free running speed (at full voltage)}} = \frac{\text{corresponding back E.M F.}}{\text{back E.M F when free running}}$$

EXAMPLE.—Suppose it is desired to calculate the starting rheostat steps for the L.N.W.R motors whose characteristic curves are shown in Fig. 23. The line voltage is 575 volts and the motor resistance (cold) is ·0615 ohm per motor. There are to be 5 series and 4 parallel notches. First take a piece of squared paper and transfer to it the speed-current curve from Fig. 23, choosing suitable scales. This represents the behaviour of the motor when free running, i e in full parallel. It is next necessary to draw in a similar curve for the motor when operating in full series, which is done by calculating a number of points as follows. Take any current value, e.g. 100 amps. Now the Ir or copper drop per motor at 100 amps will be $100 \times \cdot 0615 = 6{\cdot}15$ volts per motor The voltage across the motor terminals in full series will be half the line voltage, i.e. 287·5 volts, and the back E.M.F. per motor must therefore be (volts applied — copper drop) $= 287{\cdot}5 - 6{\cdot}15 = 281$ volts. Now reading from the motor (free running) curve, it is seen that at 100 amps. the free running speed is 46 m.p.h. The Ir drop will be as before 6·15 volts, and the free running back E.M F. is therefore $575 - 6{\cdot}15 = 569$ volts The series speed will therefore be ·—

$$\frac{\text{Series back E.M F}}{\text{free running back E M F.}} \times \text{free running speed}$$

$$= \frac{281}{569} \times 46 = 22{\cdot}7 \text{ m.p.h.}$$

This gives the first point in the curve. Repeating the process for other current values, as has been done in the following table, gives us a number of points from which the full series curve can be plotted as shown on Fig 43.

Calculation of Full Series Curve.

Amps per Motor	*Motor Ir Drop volts*	*Back E M F volts*	*Free-running Speed m p h*	*Back E M F. at Free-Running Speed m p h*	*Speed in Full series m p h.*
100	6	281	46	569	22·7
150	9	278	37	566	18·15
200	12	275	31	563	15·15
250	15	272	28	560	13·6
300	18	269	26·5	557	12 8
350	21·5	266	25	554	12
400	24 6	263	23·5	549	11·2
450	27·7	260	23	547	10·94
500	31	257	22·5	544	10 65

We must now determine the current on the first notch. In the present case no "switching" (shunting) notch is to be provided to allow of a gentle start for shunting purposes To get the requisite acceleration of the train we need (cf. Chap. III) an average starting current of 350 amps. Allowing for current rushes on each notch being about 15 per cent. above the mean, the initial current would be about 402 amps , but as the mean is generally less in parallel than series we shall allow a further 10 per cent. to compensate for this and the initial current will be taken as 450 amps.

The resistance of circuit on first notch

$$= \frac{575 \text{ volts}}{450 \text{ amps}} = 1{\cdot}278 \text{ ohms},$$

which is made up of the complete rheostat and the resistance of two motors, which latter is $2 \times {\cdot}0615 = {\cdot}123$ ohms.

Hence total rheostat resistance $= 1{\cdot}278 - {\cdot}123 = 1{\cdot}155$ ohms We may consider half of this, i.e. ·577 ohms as being in series with each motor and must now draw in the speed curve corresponding to a resistance of ·577 ohms permanently in series with the motor. The points may be calculated on the same basis as for full series, thus for a current of 100 amps the voltage drop in the rheostat will be $100 \times {\cdot}577 = 57{\cdot}7$ volts per motor ; motor *Ir* drop being 6·15 volts as before. The motors being in series,

the pressure across each motor and its rheostat must be 287·5 volts and of this the rheostat and motor copper drop accounts for $57{\cdot}7 + 6{\cdot}1 = 63{\cdot}8$ volts, so that the remainder must represent the back E.M F , i e $287{\cdot}5 - 63\ 8 = 223{\cdot}7$ volts.

The speed will therefore be

$$\frac{\text{back E.M F.}}{\text{free running back E M F.}} \times \text{free running speed}$$

$$= \frac{223{\cdot}7}{569} \times 46 = 18{\cdot}1 \text{ m.p h.}$$

Repeating this process for other current values will give a series of points which can be plotted to give the first notching curve shown on Fig. 43 The calculations are tabulated for reference below .—

Calculation of 1st Series Notching Curve.

Amps. motor	*Drop in Rheostat volts*	*Back E M F volts.*	*Speed m p h*
100	58	223	18·1
150	86	192	12·6
200	115	160	8·8
250	144	128	6·4
300	173	96	4·6
350	202	64	2·9
400	230	32	1·37
450	260	0	0

Since with this equipment it has been decided to use five series notches, we have to draw in three other notching curves between the first and the full series curves. If we select 320 amps. for the setting of our current limit relay, for a first trial, we may mark the point A where the current on the first notching curve falls to 320. At this point the relay operates and allows a further section of resistance to be cut out, the current rising suddenly to 450 amps. again at point 2. Given this first point on the second notching curve, we can construct the remainder of the curve by calculation as before, first determining the rheostat value on this second notch. Point 2 at 450 amps. represents a speed of 4 m.p h.

Back E.M.F.

$$= \frac{\text{speed}}{\text{free running speed}} \times \text{free running E.M F.} = \frac{4}{23} \times 547$$

$$= 95 \text{ volts.}$$

Motor Ir drop is $450 \times {\cdot}0615 = 27{\cdot}7$ volts

The rheostat drop is therefore 287·5—95—27·7 = 164·8 volts. Resistance of rheostat $= \frac{164 \cdot 8}{450} = \cdot 366$ ohms.

We have now all the data for drawing in the 2nd notching curve, the calculations being shown tabulated in table below. It now remains to draw in the 3rd and 4th notching curves and it will be evident that the slope of the curves lies between 1A and 5E. The relay will operate again at 320 amps. on the 2nd notching curve and the point B can be projected across to give point 3 on the 3rd notching curve. It will now be easy to estimate the slope of 3C, to project C across to point 4 and draw 4D If D projected across to the full series curve intersects it at about 450 amps. the points 3 and 4 will be about right and the 3rd and 4th notching curves can be calculated accurately and drawn in.

The following tables show the calculations for the 2nd, 3rd and 4th notching curves :—

Point	*Speed at 450 amps.*	*Back E M F.*	*Rheostat Drop*	*Resistance of Rheostat.*
2	4 m p.h.	95 volts.	164·8 volts	·366 ohms
3	7 „	166 5 „	93 3 „	·207 „
4	9 2 „	219 „	41 „	·091 „

Remaining Series Notching Curves.

Amps. per Motor.	Motor Ir Drop Volts.	Drop in Rheostat.			Back E M F			Free Running		Actual Speed		
		2nd Notch.	3rd Notch.	4th Notch.	2nd Notch.	3rd Notch.	4th Notch.	Speed. m p h	Back E M F Volts	2nd Notch	3rd Notch.	4th Notch.
250	15	91	52	23	181	220	249	28	560	9	11	12 45
300	18	109	62	27	160	207	242	26 5	557	7 6	9 8	11·5
350	21·5	127	73	32	139	194	234	25	554	6·3	8·8	10·5
400	26	146	83	36·5	115	178	225	23·5	549	4 9	7 6	9 6

The etched part of these curves will show the actual variation of current and speed on each notch. We may tabulate as follows :—

Controller Notch.	Rheostat per Motor Ohms.	Total Rheostat in Circuit Ohms	Total Rheostat in Fig. 34.	By Subtraction
1	·577	1·154	$(R_5–R_1) + (R_6–R_9)$	$(R_2–R_1) = ·422\omega$
2	·366	·732	$(R_5–R_2) + (R_6–R_9)$	$(R_3–R_2) = (R_6–R_7) = ·159\omega$
3	207	414	$(R_6–R_3) + (R_7–R_9)$	$(R_4–R_3) = (R_7–R_8) = ·116\omega$
4	091	·182	$(R_5–R_4) + (R_8–R_9)$	$(R_5–R_4) = (R_8–R_9) = 091\omega$
5	0	0	0	0 0

The lettering above refers to the rheostat numeration given in the Power Circuit Diagram for this system, Fig. 34. $(R_5–R_1)$ is intended to be read as (R_5 to R_1), etc. The circuits in parallel are :—

Notch.	No. 1 Motor.	No. 2 Motor.	Notch	No 1 Motor	No 2 Motor
b	$(R_5–R_1) = 788\omega$	$(R_6–R_9) = ·366\omega$	8	$(R_5–R_4) = 091\omega$	$(R_8–R_9) = ·091\omega$
6	$(R_5–R_2) = ·366\omega$	$(R_6–R_9) = 366\omega$	9	0	0
7	$(R_5–R_3) = ·207\omega$	$(R_7–R_9) = ·207\omega$			

With this type of control the next point "*a*" is a mere re-arrangement of contactors with motors still in full series and the current falls off down the series curve while point "*a*" is being passed through. On point "*b*" as soon as No. 11 contactor is out the two motors are placed in parallel and their circuits are for a moment unbalanced, i.e. No. 1 motor has $(R_5–R_1)$ ·788 ohms in series with it while No 2 motor has $(R_6–R_9)$ ·366 ohms in series with it. On notch 6 $(R_2–R_1)$ is cut out and each motor has ·366 ohms resistance, the two remaining notches 7, 8 and 9 cutting out equal steps for each.

The calculation of the notching curves in parallel is done exactly as for series notches, remembering that the line pressure is now the full 575 volts For example, at 250 amps in the 6th notch with ·366 ohms of resistance, the rheostat drop will be 91 volts, motor I*r* drop 15 volts, hence back E M F. will be 575 — 91 — 15 = 469 volts, and the speed will be $\frac{469}{560} \times 28 = 23{\cdot}4$ m p h. The following table shows the calculations.

Parallel Notching Curve.

Amps per Motor	Motor Drop Volts	Drop in Rheostat.				Back E M F				Free Running		Actual Speed m p h			
		b Notch.	6th Notch.	7th Notch.	8th Notch	*b* Notch.	6th Notch	7th Notch.	8th Notch	Speed m p h	Back E M F Volts	*b* Notch	6th Notch	7th Notch	8th Notch
250	15 4	197	91	52	23	363	469	508	537	28	560	18 15	23 4	25 4	26 8
300	18 45	237	109	62	27	320	448	495	530	26 5	557	15 25	21 4	23 6	25 25
350	21·5	276	127	72	32	278	427	481	522	25	554	12 6	19 3	21 7	23·5
400	24 6	316	146	83	37	233	403	466	512	23 5	549	10	17 25	20	21 9
450	27·7	355	164	93	41	192	384	454	506	23	547	8	16 2	19 1	21 3

The time in the full series curve while point "*a*" is being reached may be found from a time basis. Thus, the controller takes 18 secs to reach full parallel when testing the controller without current on the motors, which represents 1·6 secs. per notch. The full series point is reached at 12 secs. (*see* Fig. 17) and the "*a*" point will therefore take a further 1·6 secs. or 13 6 secs. in all. From the speed curve (Fig 24) this represents 15 m.p.h., and we may therefore say that the current will fall along the full series curve until 15 m p h is reached, which occurs at 210 amps. It will then leap up to the "*b*" point curve, which it reaches at a point below the setting of the relay. The controller will pause on "*b*" point for 1·6 secs reaching the 6th point after 15 2 secs. which corresponds to 16 2 m.p h.

The etched lines Fig 43 show the actual variation of current with the limit set at 320 amps. It will be seen that the peak values of current are lower in parallel than in series, which is always the case when the same rheostats are used again and this will result in the average acceleration being correspondingly lower in parallel The low mean current in passing from series to parallel results in a slight falling off of acceleration and speed, as can be seen in the acceleration chart Fig. 10 and the speed curve Fig 11 integrated

from it. The current on each notch must always follow the curves calculated irrespective of the time taken, e.g on a down gradient the time on each would be small and on an up gradient it would be greater, but in all cases the fluctuation of current must follow the etched lines.

It may be mentioned as a point of interest that by measuring the area enclosed by the etched curve with a planimeter and dividing it by the ordinate a very exact estimate can be obtained of the mean accelerating current, and in some cases this is well worth doing. (Cf. Chapter XIV.)

The method thus described does not involve such formidable calculations as may be suggested by the tables given, and lends itself very simply to adjustment and compromise.

Graphical Method. To some engineers a graphical method is always preferable where possible, and of the various graphical methods the one outlined in the following pages is perhaps the simplest. It is due to Mr. A. M. Buck, of the University of Illinois, and was published in the *Electric Railway Journal*, December 26, 1914, and February 13, 1915.

The speed of an electric motor varies directly with the back E.M.F. developed and inversely with the field flux. Hence the field flux is directly proportional to the back E.M.F. and inversely proportional to the speed, i e. :—

$$\varphi = \frac{\mathrm{E} - \mathrm{I}r}{\mathrm{k}n}$$

Where φ is the flux, E the line voltage, Ir the copper drop, i.e. (current × resistance), n the speed of rotation and k a constant depending on the design of the motor.

Now since in the calculation of starting rheostats only *proportional* values of flux are required, the knowledge of k is unnecessary and the equation may be written thus .—

$$k\varphi = \frac{\mathrm{E} - \mathrm{I}r}{n}$$

From the characteristic curve of the motor and the motor resistance, it is easy to take a few values of current I, read off the corresponding value of speed either in m.p.h. or r.p m. and so calculate the value of $k\varphi$ for each.

Mark off a piece of squared paper with current in amperes as abscissæ and voltage as ordinates, and plot on it the curve of $k\varphi$ *to any convenient scale*, as shown in Fig. 44, choosing maximum and minimum values of current, I_m and I_n respectively. These

current values intersect the flux curve at φ_m and φ_n respectively. Assume φ_n and φ_m a straight line and produce it to meet the abscissæ at the point X If the limits of accelerating current have been decided, it is evidently only really necessary to calculate φ for these two values, since no use is made of the rest of the curve.

When the current is increased from I_n to I_m by reducing the resistance in the circuit, the flux increases from φ_n to φ_m. During

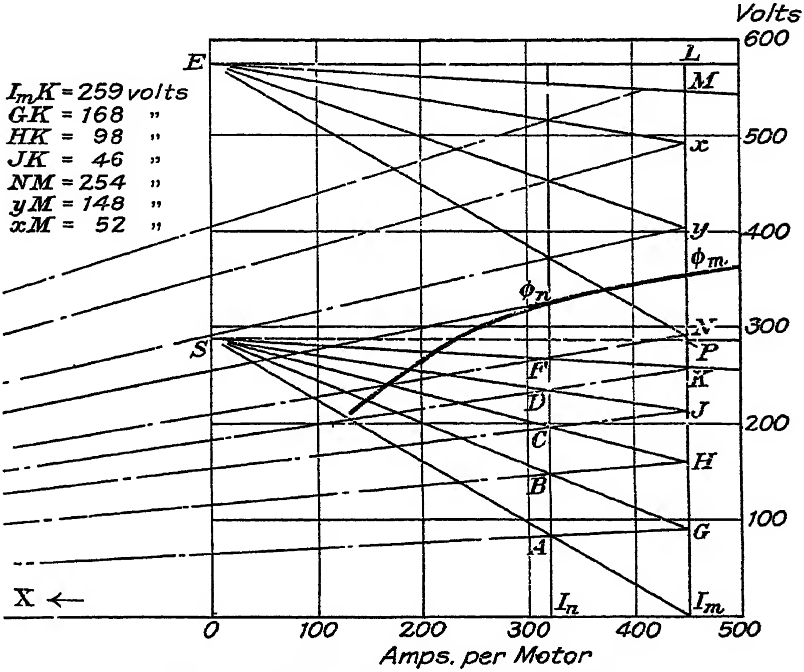


FIG. 44.—Calculation of Starting Rheostats.

the infinitesimal time required for changing the current it is evident that the speed cannot change and it must follow therefore that the back E M F. must increase owing to the greater flux, and its new value will be the back E.M F. at I_n multiplied by the ratio of fluxes, i e. :—

$$\text{back E.M F. at } I_m = \text{back E M F. at } I_n \times \frac{k\varphi_m}{k\varphi_n}.$$

For brevity call this ratio of field fluxes Q ; then

$$\text{back E.M F. at } I_m = \text{back E.M.F. at } I_n \times Q$$

In a controller using a current limit or accelerating relay the maximum and minimum values of current are to be reached on each notch and the ratio Q is a constant for each step.

Then in the figure :—

$$\frac{I_m \varphi_m}{I_n \varphi_n} = \frac{I_m K}{I_n D} = \frac{I_m J}{I_n C} \text{ etc.} = Q,$$

since all the triangles whose apexes pass through the point "X" divide parallel lines into proportional parts.

The point E is placed to represent full line voltage, 575 in the example shown, and S represents half line voltage, i e the voltage per motor while in series. Mark off LM and PK equal to the Ir copper drop per motor. EM and SK being joined these two lines represent the increase of copper drop with current, starting on the first notch with maximum current I_m the entire line voltage per motor is used in overcoming resistances, and this voltage is made up of the motor copper drop PK and the rheostatic drop I_m K. As soon as the armature begins to revolve a back E M F. is developed. When the motor current has fallen to I_n this back E.M F. is represented by the ordinate I_n A, the line I_m S being drawn through S, for evidently there will be no resistance or copper drop at zero current When the motor current has fallen to I_n the controller must allow another notch to cut out a section of resistance to allow the current to rise again to I_m. Since I_nA is the back E.M.F. at I_n, it follows that it must increase by the ratio Q when current is increased to I_n so rapidly that the motor does not have time to change its speed Join XA and produce to intersect the I_m line in G. Then I_m G represents the back E M.F. at this point, GK the rheostatic drop and KP the motor copper drop as before. The ohmic value of the rheostat at this point is found by dividing GK volts by I_m amps. Repeat for subsequent points by joining FS, project XB to H, etc., until the full series line SK is reached It must be remembered that all these resistance values are for one motor and the total resistance for two motors will be double these values in each case. Project XF to N. On changing from series to parallel, the back E.M F. per motor is I_n F just before breaking and I_m N immediately after the reconnection has been made. In series, the back E M.F.'s of the two motors add, while in parallel they do not. The residue NM must therefore be consumed in external resistance. On the first parallel point the resistance must then be $\frac{NM}{I_m}$ per motor. Join EN and continue the projecting process

until the line EM is reached The motors are now in full parallel across the line and from this point onward the normal characteristic curves of motor performance apply

If it is desired to change the current limits at any stage of these operations, for example when the resistances in parallel have to be the same as in series, the location of the point X will have to be varied to correspond to the new current limits For small changes the location of X may be assumed constant without introducing an appreciable error.

In using this method, if a definite number of steps is called for, as is usually the case, the values of I_m and I_n must be found by trial, but such trials can be very quickly made

It is instructive to compare Fig 44 with Fig. 43. The results obtained in series are approximately the same by the two methods, but in parallel Fig 44 gives the theoretically correct resistance values, while the notching curves of Fig 43 show the actual current variations when the same resistances are used in parallel as in series.

In both these methods, calculations have been made for two motors in series-parallel. If the controller equipment is to be used on four motors, i.e. two groups each of two in series, it must be remembered that the motor resistance to be used is double that of a single machine and the calculations must be modified accordingly.

Temperature Rise of Rheostats. Although the difference is not great, it is advisable to base rheostat calculations on the hot rather than the cold resistance of the motors ; further, in designing the actual rheostat grids the calculated values should be taken as the resistances when hot. The resistance of the L N.W.R motor, which is 0615 ohm at 20° C., increases to ·0761 ohms at 80° C. The method of correcting for temperature is shown in Chapter XII (p. 257). Unless the contrary is stated, motor characteristic curves are to be taken as referring to the standard temperature of 75° C. (Cf. Chapter XII, p. 253)

The maximum permissible temperature for rheostats will vary with conditions, but a representative case for rheostats placed beneath the car allowed for an average temperature rise of 170° C., based upon 25 starts per hour. The actual resistances were : 3 00 ohms at 20° C., and 3·224 ohms at 190° C. The temperature coefficient for the particular grade of cast iron used in these grids, calculated from the above resistances, is a = ·000443 per 1° C

CHAPTER VI

DIRECT CURRENT TRACTION MOTORS

It is well known that of the three types of D C motor available—series, shunt and compound—the series motor is in almost universal use and it will be well to examine the reason for this.

The Shunt Motor. The shunt wound motor is inherently a constant speed machine, i.e. its speed is almost independent of the load. It is this characteristic which makes it so suitable a motor for industrial work, such as driving a line of shafting at a constant speed irrespective of load fluctuations and the motor will not over-speed if its belt comes off. Such a motor, if used for traction work, would produce the curious effect of driving the train at a practically constant speed on the level, up and down hill. This would produce very heavy loading on the motors when travelling up a gradient and an objectionable peak load on the sub-stations

The torque of any motor is the interaction of the field flux and armature flux The effective E M F , i.e. line volts minus back E.M F., determines the motor current If the load on a shunt motor be varied, the variation will result in a variation of armature current and hence of armature flux, since the shunt field remains constant Since the line voltage and the armature resistance remain constant, it is the back E.M.F. which must vary for there to be a variation in armature current, and since the field flux remains constant the speed will have to vary for there to be a variation of the back E.M F. The extent of this speed variation can be seen in an actual example.

A small 100-volt shunt motor has an armature resistance of 0·2 ohm, its full load current being 10 amps. When running at a quarter of full load, i e with 2·5 amps through the armature, the effective E M.F. is $\cdot 2 \times 2\cdot 5 = 0\cdot 5$ volts and the back E.M F. is therefore 99·5 volts. The speed is therefore proportional to 99·5 volts. If the motor be now loaded to its full load of 10 amps. the effective E.M.F. becomes $\cdot 2 \times 10 = 2$ volts, the back

E.M F becomes 98 volts and the speed is proportional to 98 volts. Thus the speed drops only about 1·5 per cent between a quarter and full load, which is so small a variation as to justify the term "constant speed motor" being applied to the shunt motor, in that the speed is independent of the load for most practical purposes.

The Series Motor.

In the case of the series motor, the field flux is not constant The field and armature windings are in series with each other and hence whatever current passes through the one also passes through the other. Hence if the current through the motor be doubled, the field and armature flux will each be doubled, and since the torque is a function of the product of field and armature flux, it follows that doubling the current produces roughly four times the torque

The variation of field flux is actually not quite proportional to current but depends on the saturation curve of the field magnets ; further the damagnetising effect of the armature loading has not been considered Nevertheless the rapid increase of torque with current is one of the characteristic features of the series motor.

As to speed variation, a decrease in current causes a decrease in field flux and hence a greater increase in speed is necessary to generate a back E.M.F. suitable to the lighter load than in the case of the shunt motor.

As before, this is best realised by a numerical example. A small 100-volt series motor with a field resistance of 0·2 ohm and an armature resistance of 0·2 ohm and a full load current of 10 amps as before is working at full load. The effective E.M.F. is now 4 volts and the back E M.F. 96 volts. If now the load current be reduced to one quarter, the effective E.M.F. becomes 1 volt and the back E.M.F. would require to be 99 volts with a constant field flux. But the field flux is not constant, the reduction of armature current to one quarter has caused a reduction of series field current and hence of field flux to one quarter. Then to generate 99 volts back E M.F. the armature must revolve at four times the speed corresponding to 99 volts back E M.F. The speed variation between full load and quarter load is therefore proportional to values of 99 to 396, or four times the speed at quarter load.

Effect of Wear of Wheels. The wheels of a train have to be re-turned whenever the flanges wear too sharp for safety, about 1½ in. radial depth, i.e. 3 in. diameter being usually allowed for

re-turning before the wheel must be re-tyred. It may, therefore, frequently happen that driving wheels of different diameters are operating on the same train, and it is of interest to see how the load is shared between them. For a given speed of the train it follows that the wheel with the larger diameter makes less revolutions per minute than the smaller wheel and will therefore take a larger current Fig 45 shows the characteristic curves for the G.E 237 motors with full field which operate in

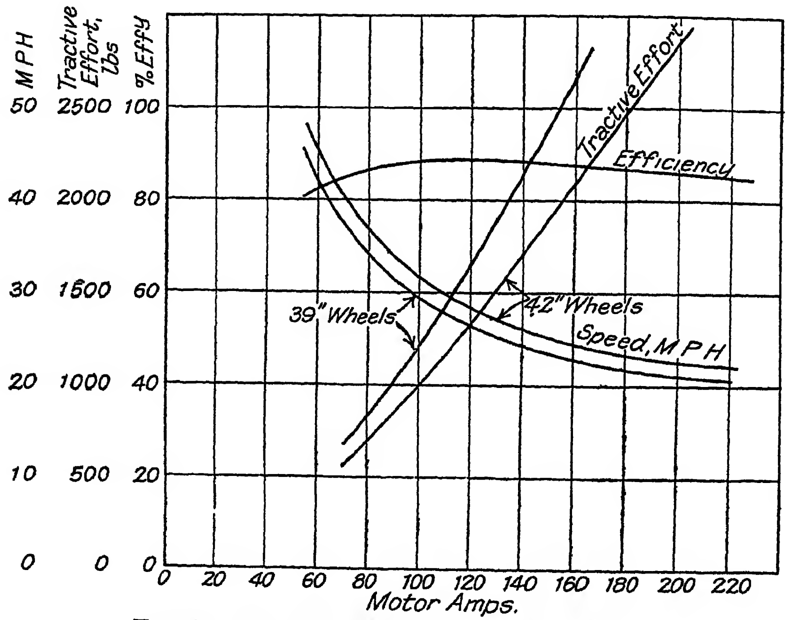


FIG 45 —G.E. 237 (Melbourne) Motor Curves

groups of two in series on 1,500 volts on the Victorian Railways (Australia). The speed is based on 42-in. wheels and a gear ratio of 74 to 23, the curves being calculated for a copper temperature of 75° C. Taking any point on the speed curve, e.g. at 35 m.p.h , the current is 87 amps. If one pair of driving wheels is worn down to 39 in , the speed of its motor will be reduced to $\frac{39}{42}$ of the normal revolutions per minute, and if this is to be plotted on the speed scale, the actual speed correspond to $\frac{39}{42} \times 35$ m.p h. $= \cdot 93 \times 35 = 32{\cdot}5$ m.p.h. At each other current value, the corresponding motor speed will be reduced to ·93 of the curve

speed. A new curve plotted from points obtained in this way is shown in Fig 45 with the original speed curve beside it for comparison Projecting across at 30 m p.h. it is seen that the currents taken by the motors are 108 amps on the 42-in. and 96 amps on the 39-in wheels, the difference becoming greater as the speed falls. Remembering that the heating effect is proportional to the square of the current, it will be seen that the difference of wheel diameter has quite an appreciable effect on the temperature rise, which may often explain the discrepancy between the temperatures obtained from a number of motors on the same train. The difference is, however, not great enough to warrant any step being taken to avoid it in practice

The tractive effort varies with current and will therefore be higher on the slower motor. In the above example at 35 m p h. or 87 amps. the tractive effort is 800 lbs , while at the speed of 32·5 m p h. for the 39-in. wheel, which corresponds to 35 m p h. for the 42-in the tractive effort is 960 lbs The two tractive effort curves are shown in Fig. 45 for comparison. If there are on a train an equal number of 42- and 39-in. wheels, the average tractive effort will be the mean of the two curves, while for any other proportion the arithmetical average must be taken. For example, at 35 m p h. the mean tractive effort per motor of a car containing 3 driving wheels of 42 in. and 1 of 39 in. would be $\frac{(3 \times 800) + 960}{4} = 840$ lbs.

The worst condition of overloading will clearly be met with in the case of one new wheel on a long train of undersized wheels.

The effect of wheel wear is much more serious in the case of shunt motors Fig 46 shows typical characteristic curves for an American General Electric Co 's interpole shunt wound motor, made in various sizes up to 200 h p. Converting speed in r p m into speed in m p h. using a gear ratio as before of 58/18 and wheel diameters of 41 and 39, the two speed curves shown in Fig. 47 can be deduced. Taking any speed, e g 31·43 m.p.h. it is seen that the motor input for the 41- and 39-inch wheels is 127 and 31 per cent respectively, i e with only 2 inches difference of diameter larger wheel takes 4·1 times the current of the smaller one ; further it will be seen that at speeds above 32 m.p h. the motor with the smaller wheel will take less than no input, i.e. will act as a brake on the train The speed variation above normal which can be obtained by weakening the field current is only 15 per cent. with safe commutation and the various character-

istics which have still to be discussed should show convincingly the general unsuitability of the shunt motor for traction use.

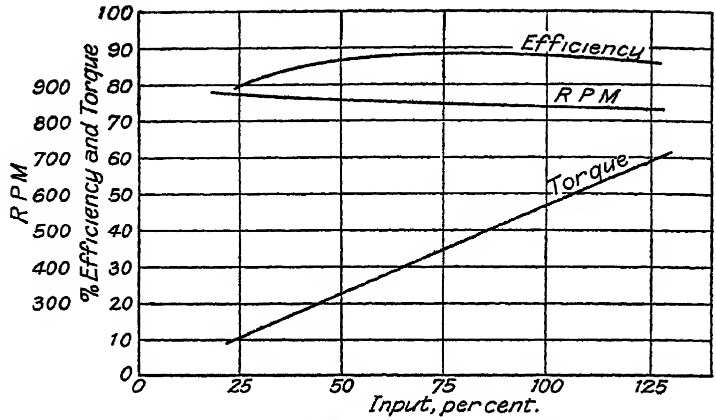


FIG. 46.—Shunt Motor Characteristics

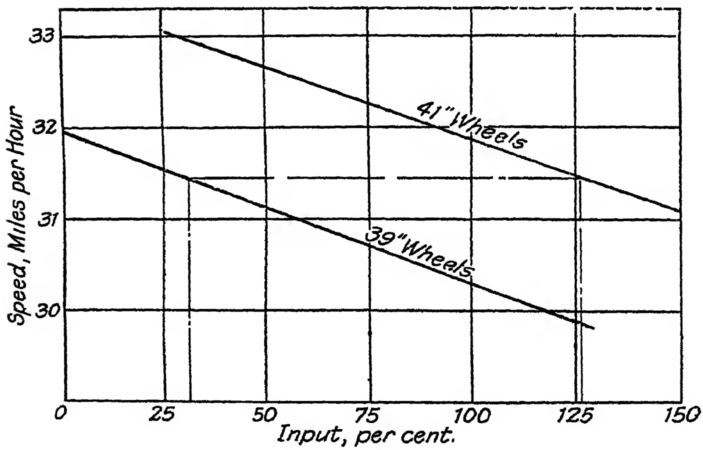


FIG. 47.—Shunt Motor Speeds.

Since the characteristics of the series machine are so very well adapted to the purpose, there is no advantage to be gained by compounding, and the simple series motor with interpoles leaves little to be desired.

Effect of Variation of Voltage. Traction motors are liable to two forms of sudden voltage variation, viz. :—

(*a*) Pressure rises or surges, due to switching off large currents, or to opening short circuits, and

(*b*) Sudden interruptions of pressure caused by running over gaps in conductor rails at crossings, or over section insulators in the rail or overhead line.

Both of these represent operating conditions peculiar to traction service and have an important bearing on the type of motor used and on its general design.

Dealing first with pressure rises :—

The rise in pressure may be caused by the sudden switching off of power on a train which is on the same electrical section, or by the sudden opening of a momentary short circuit on the track. In such cases, the initial value of the current rush depends solely upon the impedance of the motor, but its duration depends on the rate of building up of back E M F. Now the series motor has naturally a high impedance, the fields and armature being in series, and hence the initial current rush will be much lower than in the case of a shunt motor ; further, since the effect of the current rush will be to strengthen the field, the rate of increase of back E.M.F. will be high. In effect, therefore, both as regards initial value of the current surge and its duration the series motor has the advantage, as also from the fact that the strengthening of the field makes commutation more easy and hence reduces the liability to flash over. Shunt motors, from their lower impedance, produce greater current surges, which are also of longer duration, and as the commutating power is not increased, flash-over is much more likely to occur. There is also the risk of slipping the wheels. A modern series motor can safely negotiate a current surge of 80 per cent. above normal current without flash-over

Sudden interruptions of pressure, when the pressure is momentarily cut off and restored at full voltage, produce a somewhat different effect. On switching off, the shunt motor continues to generate a back E.M F., slowly falling as the speed falls, while in the case of the series motor the back E.M.F. ceases almost immediately. This fact will no doubt be familiar to the reader, and is evident when it is considered that the passage of a current, such as would be possible where a circuit of lamps or contactor coils are across the line from which the motors are fed, has the effect of destroying what residual field flux may remain. On restoring the supply voltage, the current surge and its duration

depend on the rate of building up back E.M F. as before, but the shunt machine starts with the advantage of having a high back E.M F. ready to play its part The series motor has the additional disadvantage that the solid steel field system prevents the field flux from increasing as rapidly as the current and hence the large current has momentarily to be commutated by a relatively weak field The higher impedance of the series motor, however, is greatly in its favour and in a very few moments the rapidly increasing flux eases the situation and by suitable design this operating condition can be provided for.

Features in Electrical Design of Series Motors. From the previous remarks it will be evident that the following features will promote good commutation under difficult conditions :—

(1) A relatively strong field and weak armature ampere turns An increase in current strength will then increase the field flux proportionally more than the armature and thus improve commutating conditions. Interpoles assist the design by permitting good commutation without too high a field strength, and the lessened field flux reduces commutation losses, eddy currents and core losses. On the other hand the lesser field flux reduces the resistance of the motor to surges and the design must strike the best compromise between these conflicting conditions. The value of the field ampere turns may be as much as two to three times the armature ampere turns in a modern interpole motor.

(2) A large number of commutator segments to keep the reactance voltage per segment as low as possible.

(3) A large neutral commutating zone, since no adjustment of brush position is possible and the motor is required to operate equally in both directions

(4) Laminated field poles to prevent eddy currents and so to allow the field flux to build up as quickly as possible.

(5) No solid spool bodies which can form short-circuited turns round the field and so produce eddy currents and retard the field flux.

The success of these devices to secure good commutation is shown in the British Standard Specification for D.C. traction motors, which requires all motors to work in either direction from no load to 30 per cent. above the rated full load with fixed brushes without injurious sparking (*see* Chapter XII). In practice, motors will often deal successfully with as much as 100 per cent. overload without even visible sparking A flash-over may occur, however, if the commutator is allowed to become rough or unevenly worn, or if the track is rough and causes

excessive vibration, especially if at the same time the spring pressure on the brushes is too weak The brushes must be fixed exactly in the geometrical neutral position. Up to the present there has been no successful introduction of ball or roller bearings for traction motors and the bearing used is therefore of the usual shell type and is liable to wear. Such wear causes a displacement of the armature centre and hence produces an unequal air gap, the gap being greater on top of the armature than below it. This difficulty is obviated by the use of a two-circuit wave winding for the armature, which has the advantage of producing an electrical balance of the two circuits even with an unbalanced magnetic field It is universal practice to adopt four poles on all geared traction motors and this, with a two-circuit wave winding, allows of the use of only two sets of brushes which are readily accessible for inspection from the floor of the car For large high voltage motors, e g the Metropolitan Vickers 360 h p motors at 1,500 volts for the Sydney Railway, four sets of brushes are being fitted in order to guard against the increased liability to flash-over caused by the high voltage

Commutators. The commutator is made with as great a diameter as possible in order to allow as great a distance as possible between the positive and negative brush arms, to allow a reasonable width of commutator segment and also for cooling. About $\frac{3}{4}$-in. radial depth is usually allowed for wear.

The commutator must be strongly built to withstand heavy vibration and high centrifugal force. The peripheral speed of the face of the commutator should not exceed 8,000 ft per minute. In the case of the L.N W.R. motors, the maximum speed of the train was specified to be 55 miles per hour. The commutator diameter is $16\frac{15}{16}$ ins., gear ratio 3·33, and the wheels when new are $43\frac{5}{8}$ ins. diameter When the wheels are worn out to the scrapping point the diameter may be only 39 ins. If such a wheel is operating on a train moving at 55 m p.h. the speed of the armature will be $\dfrac{55 \times 88 \times 12 \times 3{\cdot}33}{\pi \times 39} = 1{,}580$ r.p.m. and the peripheral speed of the commutator $1{,}580 \times \dfrac{16{\cdot}94 \times \pi}{12} = 7{,}000$ ft. per minute. In most ways the design of the commutator follows the general practice for stationary motors, the micas between segments being recessed about $\frac{1}{16}$-in. below the surface. The Vee rings must be so shaped as to allow the bearing to snug inside the commutator, on account of the limited axial length available.

Mechanical Features. The field yoke or carcass of traction motors is always of cast steel to combine high permeability with strength and minimum weight. The end shields which carry the bearings, the Vee rings of the commutator and the spider on which the field laminations are built are also of cast steel or malleable iron Some light-weight motors have been developed for tramway use in which the yoke and some other parts are of pressed steel, but this design has not been adopted for heavy traction.

Field and Interpole Coils. Field windings are usually of copper strap, wound flat with a spacing of micanite between turns. The whole winding is taped up and impregnated with a bitumen or gum compound to fill up all interstices, forming a solid mass to keep out moisture and improve the heat conducting and radiating power of the whole A flat steel spring washer is inserted between the field coils and the frame and the final tightening up takes place against the spring, a measure made necessary by the vibration to which the motor is subjected The interpoles are of solid steel, not laminated, and the winding is of rectangular section copper. The interpole coils should be connected to the negative side of the armature in an earth return system, since otherwise the enormous mechanical stresses set up in them by a flash-over may distort them.

Nose Suspension. In order to use a high-speed motor and so to obtain a minimum weight per horse-power, it is usual to drive the wheels through single reduction spur gearing. The

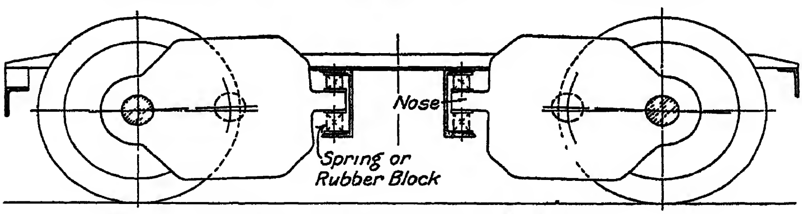


FIG. 48.—Nose Suspension of Motors

distance between the centres of pinion and gear wheel has to be maintained rigidly exact, and this is done by mounting a bearing in the motor case, known as a suspension bearing, on the axle of the driving wheels On the other side of the motor case a projecting "nose" is cast and this nose is fixed on the bogie transom with a stiff spring above and below it This "nose suspension" is shown diagramatically in Fig. 48, and it will

be seen that part of the motor weight is spring borne, the remainder being directly on the driving wheels

Fig 48 shows a bogie with two nose-suspended motors in place. There are several other forms of suspension; e g the quill drive in which the motor-armature is on a hollow "quill" inside which is the axle of the wheel, and the Brown-Boveri Individual Drive. Simplest of all is the gearless drive, in which the armatures are mounted directly on the axles of the wheels, but all of these are only used on locomotives and therefore do not come within the scope of this book. For multiple unit trains the nose suspension is practically universal.

Tractive Effort. The tractive effort of a railway motor is always referred to as the force developed at the tread of the

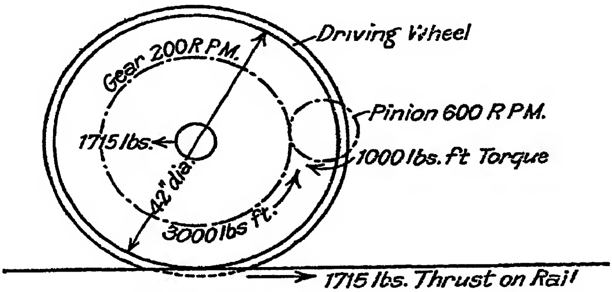


FIG 49—Torque and Tractive Effort Gear Ratio, 1 3.

driving wheels. This is a more convenient form for calculation purposes than regarding it as a torque, and it is derived from the torque quite simply, as shown in Fig. 49. Suppose motor torque is 1,000 lbs -ft., i.e. 1,000 lbs force at 1 ft. radius. The torque on the gear wheel will then be 3,000 lbs.-ft, if the gear ratio is 1 to 3, and the tractive effort at the tread of the wheels is exerted at 21 ins. or 1·75 ft. radius and its amount is therefore $\frac{3,000}{1 \cdot 75} = 1,715$ lbs.

That this tractive effort produces an equal and opposite reaction on the rails, tending to thrust the rails away, is quite obvious, but it may not be quite so obvious that the tractive effort is transmitted to the car through the axle boxes and therefore produces a force on these boxes equal to the tractive effort at the tread of the wheels.

The load on the teeth of the gear wheel produces a torque on

the driving wheel and not a pure "couple." The laws of mechanics tell us that a torque is balanced by a couple and a force, the truth of which is illustrated by Fig 50 A car is placed upon rails, and a rope is coiled round one wheel, whose tread is suitably lengthened to allow free space for the rope A weight W lbs., of magnitude just sufficient to overcome the frictional resistance of the car, hangs from the end of the rope which passes over a pulley of radius r. The pulley must be considered as fixed to, and moving with, the car The pull of W is therefore exerted at the tread of the driving wheel. If W is allowed to fall and so to pull the car forward a length equal to one revolution of the wheel, the work done will be $2\pi r$W ft.-lbs Suppose now the rope be removed and a force of F lbs, just sufficient to move the car, applied to the body of the car and hence to the axles and maintained while the car moves forward the same distance as

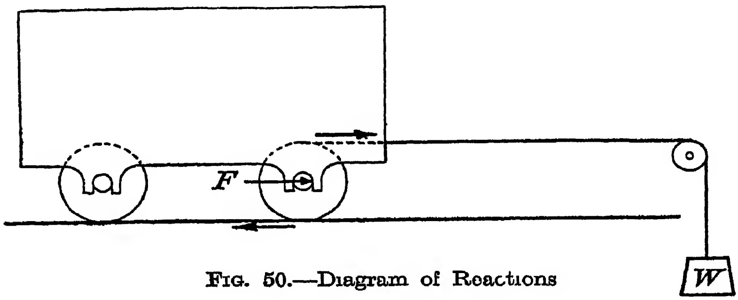


FIG. 50.—Diagram of Reactions

before The work done will be $2\pi r$F ft.-lbs.. and since the work done in the two cases must be equal, it follows that F = W, i.e. the tractive effort developed by the motors and measured at the tread of the wheels produces an equal horizontal tractive effort on the axle boxes of the car and hence on the draw bar (It will have been noticed that in these drawings one wheel is used diagramatically to represent a pair of wheels.) It must be borne in mind when speaking of the tractive effort of a locomotive that the weight of the locomotive has itself to be driven and hence the draw-bar pull will actually be the sum total of the motor tractive efforts less the frictional resistance of the locomotive itself. This distinction is by no means always made in stating the tractive effort of a locomotive

Gears and Pinions.—Pinions are now invariably cut from solid forged steel, and are usually heat treated after the

teeth have been cut. They are often keyed to the armature shaft, the bore being tapered to about 1 in 10, and are boiled before being put on, boiling being adopted as the method of heating since it prevents the possibility of a temperature being reached which might injure the temper of the steel. This causes expansion and on cooling a certain amount of shrinking takes place. The gear wheels are usually solid forged steel or case-hardened cast steel, split gears having now been abandoned for heavy work. The gear is pressed on to its seating on the axle, or better to a seating on the wheel centre. A well-known gear is made by the Cincinatti (U.S.A.) Tool Steel & Gear Co., and is heat treated after machining, the effect being to produce a case-hardened surface of about $\frac{1}{8}$ to $\frac{3}{16}$ in. thickness, the hard surface to resist wear and the tough interior to withstand shocks. The makers guarantee a life of 750,000 miles for the gear with a wear of only $\frac{1}{16}$ in. on the faces and a lesser amount for the pinion, the ratio of the two approximating naturally to the ratio of gear reduction.

Of the two forms of tooth profile available, the involute and the cycloidal, the involute is invariably used for traction gearing, owing chiefly to the fact that the involute tooth maintains its accuracy of rolling contact even if the wheel centres are somewhat displaced, as may occur if the bearings become worn. In addition the involute tooth is thicker at the root and hence stronger, which is a matter of importance where space is limited. There are also manufacturing advantages. The breakage of a tooth is an important matter, since it may lead to a bent armature shaft and a locked driving wheel. Since the train must be worked back to its depot with the wheels locked, the two tyres may be worn to destruction before they can be removed. The size of tooth is denoted by the diametral pitch, which is the number of teeth divided by the diameter of the pitch circle in inches, or more simply the number of teeth per inch of diameter of the pitch circle. Thus if there are to be 58 teeth of diametral pitch 2, the pitch circle diameter will be 29 ins. The diametral pitch is generally about $2\frac{1}{2}$, but pitches of $2\frac{1}{4}$ or even 2 are being used for heavy suburban work while the size may reach $1\frac{3}{4}$ for heavy locomotives. The angle of approach is usually $14\frac{1}{2}$ degrees, but 20 degrees is sometimes used.

An interesting gear development is the Maag gear, which is being manufactured for traction purposes by the Metropolitan Vickers Electrical Co. In this gear the teeth are ground to a high degree of accuracy after hardening, thus eliminating any distortion caused by tempering and giving a very perfect finished profile.

The pinion and gear are enclosed in a gear case of pressed steel, riveted or welded gear cases being also used. The gears are lubricated with a thick paste containing heavy grease and graphite, but American practice favours the use of oil, the gear case forming an oil bath.

Field Control. The speed of a shunt motor is capable of being varied by reducing the strength of the field by a rheostat in the field circuit It is not possible to achieve the same result in the same way with the series motor since the current passing through the armature must also pass through the field. The problem can however be solved in two ways, (1) by shunting the field with a rheostat and (2) by short-circuiting some of the field coils

The first method is the less satisfactory, because, with a field so shunted, a sudden pressure rise in the supply will cause the bulk of the resulting current rise to pass through the non-inductive resistance instead of the inductive field circuit, and in consequence the commutating power of the motor will be impaired. The objection could be overcome by making the rheostat inductive, but this would represent a large increase in complication, weight and cost

The other method, of bringing out tappings from the field windings and altering the connections to include less turns, is therefore preferred and is becoming increasingly popular. Its chief advantage is that it allows of motors being designed for a suitable speed for short distance runs, together with one or more extra high speeds for non-stop or long distance runs, thus allowing both short and long distance runs to be done economically with the gear ratio chosen If this could not be done, the gear ratio would have to be, for economical running, a compromise between the ratio best suited to each run. If, on the other hand, the motor control is designed to allow the motor to accelerate always to the "short field" speed as a matter of routine, an important economy results, since the motors are off the starting rheostats much earlier than would be the case with motors designed for the same maximum speed without field control.

In many cases two tappings are made in the field windings, giving a choice of full, intermediate and short field, the ratios being respectively 100, 75 and 50 per cent. A suburban railway in Oslo,* Norway, is equipped with 1,200-volt motors whose field windings are not only divided for short and full fields, but are grouped for series and parallel connections of the fields This

* E. V. Pannell, *I E E*, Vol 54, No. 258, p. 435.

gives four different running speeds, all with the motors directly on the line with full supply voltage, and results in nearly half of the controller notching being performed free of the rheostats, thus giving a good approximation to single-phase transformer tapping control. The objection to this is on the grounds of complication, the tappings must be taken of course from the windings on each of the four poles and such a number of necessarily heavy cables is difficult to find room for in the motor, besides adding to the contactors and generally complicating the control gear It is becoming standard practice to use one tapping only, taken from a point corresponding approximately to 50 per cent. of the field turns in view of the simplicity of control connection.

If the characteristic curves of a motor are known, the determination of its performance with tapped field is a matter of simple calculation. For example, Fig. 51 shows the speed and tractive effort curves for a G E. 235 railway motor. Suppose it is desired to calculate the speed and tractive effort curves for the same motor with 50 per cent. field turns. It will not be correct to say that half the field strength will produce half the torque, since the field flux is not directly proportional to the current throughout its range. The method is therefore to obtain the tractive effort per ampere from the curve and plot it to a current base. This will represent to some scale the B/H or magnetising curve of the motor, from which true proportional values can be obtained. The following table shows values of current, tractive effort and speed from the curve, the tractive effort per ampere being calculated from the first two columns.

Amps	*Tractive Effort lbs*	*Speed m p h*	*Tractive Effort per ampere. lbs*
100	1,050	32	10·5
150	2,100	25·5	14
200	3,200	22 5	16
250	4,250	21	17
300	5,350	19	17·8
350	6,400	18·5	18·3
400	7,500	18	18·75

The tractive effort per ampere is shown plotted against current in Fig. 52, and the curve represents to some scale the variation of field flux with magnetising force in ampere turns. If now the ampere turns are halved, the field flux for the halved magnetising force can be obtained from the curve For example, at 300 amps. the tractive effort per ampere with half field turns

will be that corresponding to 150 amps. with full field, i e. 14 lbs per amp The actual tractive effort will now be 300 × 14 = 4,200 lbs Other values are tabulated below.

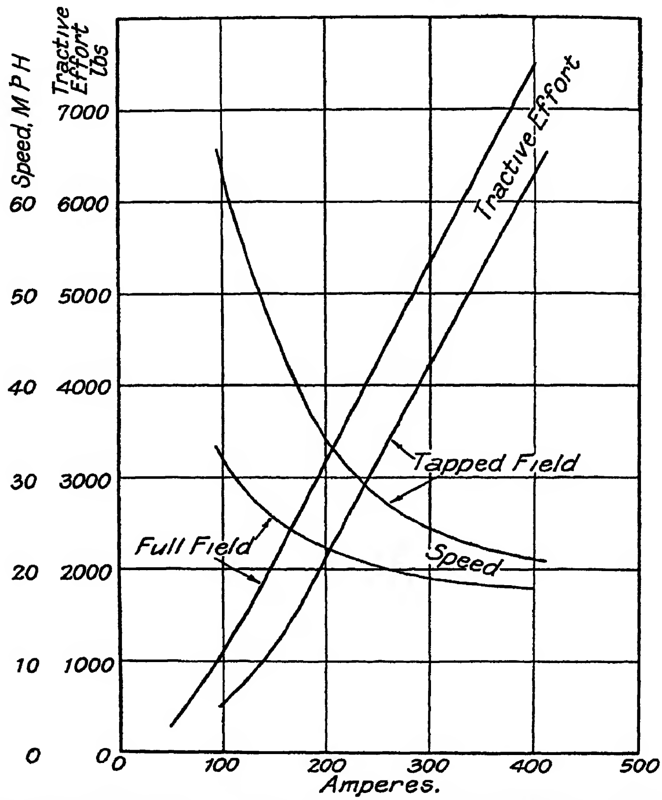


FIG. 51.—Characteristic Curves of a G.E 235 Railway Motor. 70/22 Gear, 42-in. wheels, 775 volts.

WITH 50 PER CENT. FIELD TURNS.

Amps.	*Tractive effort per amp.*	*Tractive effort. lbs.*	*Speed. m p h.*
100	5·3	530	63·3
150	7·8	1,170	45·75
200	10·5	2,100	34·3
250	12·5	3,125	28·55
300	14	4,200	24·2
350	15	5,250	22·5
400	16	6,400	21·1

From the new tractive effort thus obtained the corresponding speed can be calculated. Thus, the horse-power output for any current

$$= \frac{\text{tractive effort in lbs.} \times \text{speed in m p.h} \times 88 \times \text{efficiency}}{33{,}000}$$

Assuming that the horse-power output and efficiency with tapped field is the same as with full field, the new speed can be calculated from the above expression. It is not necessary to work out the

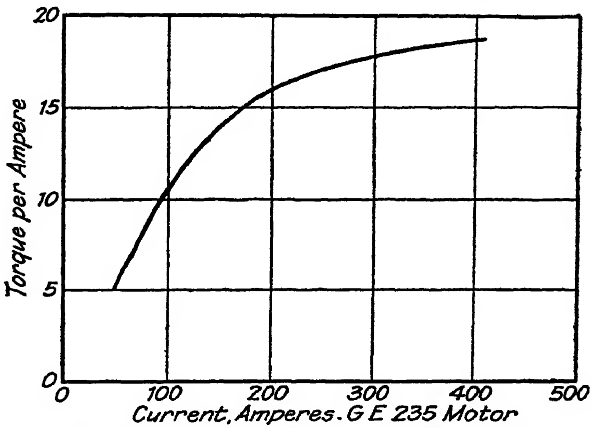


FIG. 52.—Torque per Ampere from Fig. 51.

horse-power, it is sufficient to notice that the output is proportional to tractive effort $\times$ speed.

To find therefore the speed with tapped field at 300 amps. we may say—speed required

$$= \frac{\text{tractive effort with full field}}{\text{tractive effort with tapped field}} \times \text{speed with full field}$$

$$= \frac{5{,}350}{4{,}200} \times 19 = 24{\cdot}2 \text{ m p h.}$$

The new speed values thus calculated are shown in the last column of the above table.

The argument is not exact, for owing to the smaller copper loss in the fields, the efficiency will be slightly higher than with full field, but this effect is a small one, especially at low currents, and will be to some extent balanced by increased friction due to the higher speed, and by increased core losses. The method, therefore, while not sufficiently accurate for a motor designer, who will obtain his figures from a detailed computation of losses and

from actual tests, will serve to show the nature of the calculations involved and will give a very fair approximation to the actual performance of a motor with field tapping.

A motor not originally designed for field tapping cannot easily be converted, for the working speed may already be as high as is consistent with safety of armature and gears, while the commutating qualities of the motor may not be satisfactory at the lower field strength.

Selection of Gear Ratio. The selection of a gear ratio for a given motor and schedule is a matter of great importance for economical running. The speed of a car driven by given motors at a given current and voltage and given diameter of driving wheels depends (if the small variation of train resistance be neglected) upon the gear ratio, which is the ratio of the number of teeth on the driven wheel to the number of teeth on the pinion. If this gear ratio be increased, the speed of the car at a given current will be reduced and the tractive effort increased (as in the case of an automobile on low gear).

The increased tractive effort will result in an increased acceleration or the same acceleration can be produced with a less current. If the gear ratio be reduced, the speed of the gearing will be increased, the speed of the car at a given current will be increased and the tractive effort and hence acceleration will be reduced, or the same acceleration will require more current.

With a constant accelerating current, a high gear ratio will enable the motors to reach their maximum speed quickly and thus shorten the period of running on the rheostats. The rheostat losses are therefore reduced. The speed, however, when the motors reach full parallel will be relatively low and power will have to be kept on the motors for a longer time if the schedule time is to be maintained. The average motor current is low owing to the low average speed.

If a series of speed-time curves is worked out for a given run, keeping the accelerating current constant but varying the gear ratio, it will be found (1) that there is a critical value of gear ratio at which the energy consumption for the whole run (total watt-hours per ton-mile) is a minimum, (2) that the total motor losses are lowest with the maximum gear ratio. The question of gear ratio selection has been fully discussed and a very complete series of curves calculated in the *Electric Journal* of 1908, from which paper Fig. 53 has been taken. The curves refer to a single 40-ton car over a run of 0·6 mile and apply only to the specific case, but are useful as illustrating the deductions stated.

The maximum gear ratio possible for a schedule would not be practicable because the motors would be operating at their full speed for a great proportion of the time, allowing no coasting at all, and hence there would be no margin in hand for making up lost time when required. The total energy consumption will be the most important consideration in most cases, since on it the energy cost of the railway service depends, but the method described is capable of showing the most economical gear ratio

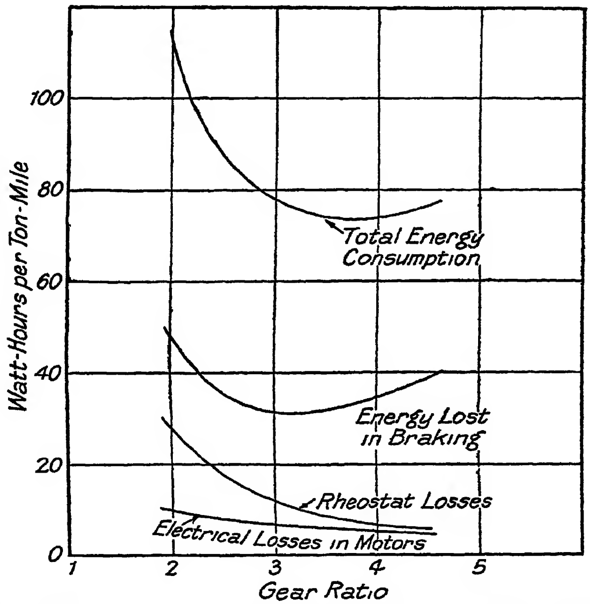


Fig. 53.—Typical Performace Curves of Car with different Gear Ratio and constant Accelerating Current.

for any given run. If the various runs are tolerably alike in character, so that their average differs little from the extremes, the method can fairly be applied, but this is usually not the case, since severe gradients, non-stop runs and short runs have all to be made with a fixed gear ratio and the selection of the most suitable is a matter calling for much engineering skill. The adoption of field control greatly helps, since it amounts practically to a change of gear ratio inside the motor, and allows the gear ratio to be chosen for a fairly high acceleration with full field, the high free running speed being obtained with field control. In

general it may be stated that the best gear ratio is the highest with which the necessary schedule can be maintained, with an allowance for low line voltage and making up lost time, without causing a dangerously high armature speed on down grades.

Too low a gear ratio with motors which would be large enough if a higher gear ratio were used causes the motors to operate on the rheostats during too great a proportion of the time, which

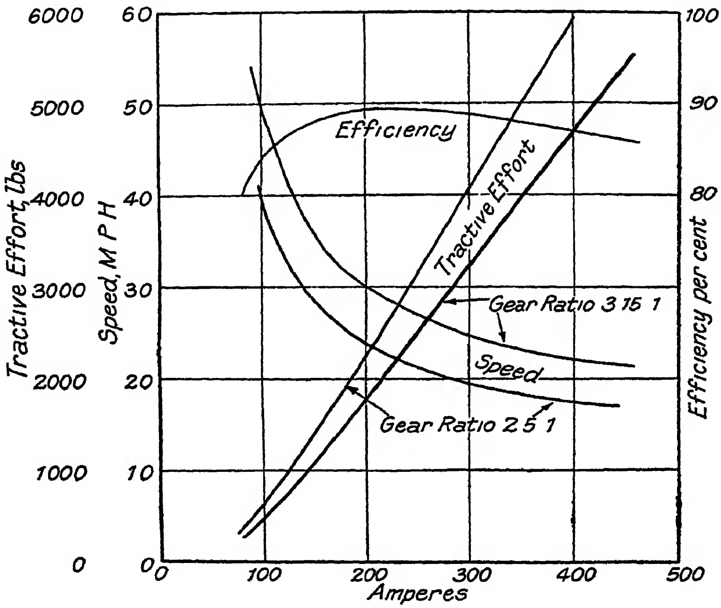


FIG. 54—Characteristic Curve of G E. 212 Motor, 63/20 Gear Ratio, 40-in. wheels, 600 volts, re-drawn for 2 5 to 1 Gear Ratio.

causes overloading and overheating of the motors, a waste of energy, and overloading of the power and sub-stations.

It will be understood that motor characteristic curves are made up to correspond with a motor temperature of 75 degrees Centigrade, for a given voltage, gear ratio and size of driving wheel. If it is required to investigate the working of a motor with any other gear ratio the alteration is easily made, since the train speed is inversely and the tractive effort is directly proportional to the gear ratio, the efficiency being practically unaltered with the change of gears. Thus Fig. 54 shows the

characteristic curves of the G E. 212 Railway Motor with a gear-ratio of 63/20, i.e 3·15 to 1. Suppose it is desired to alter this to 2·5 to 1 (assuming there are no practical difficulties) Now taking any value of current, e g. 300 amperes, the corresponding speed and tractive effort are 24·5 m p h and 3,250 lbs respectively With the gear ratio of 2 5 the speed will become $\frac{2 \cdot 5}{3 \cdot 15} \times 24 \cdot 5 = 19 \cdot 4$ m p h., while the tractive effort becomes $\frac{3 \cdot 15}{2 \cdot 5} \times 3{,}250 = 4{,}090$ lbs. By plotting a number of such points the other curves shown in Fig. 54 can be drawn.

The method of altering the motor characteristic for a change in wheel diameter is described earlier in this Chapter, and the method of correction for a change in voltage is set out fully in Chapter V.

Efficiency Tests on D.C. Series Motors. The simplest method of making a heating or efficiency test on D.C. series

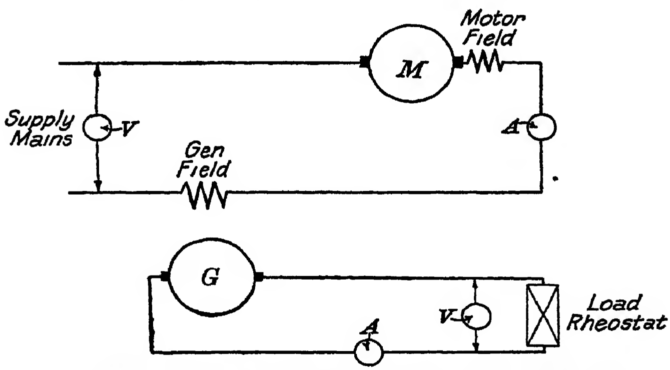


FIG. 55.—Loading Test on Two D.C Series Motors.

motors is to take two motors of the same type, place on a stand geared together or with a clamp over their pinions, and connect up as shown in Fig. 55, so that one motor drives the other as a generator and feeds power into a rheostat The motor M is started up by means of a water or other rheostat, its current passing in series through the field of motor G which is acting as a generator The armature of the generator is connected direct to a water-rheostat which must be switched on before starting or the motor will be running light and will race.

Since the fields are in series, the flux of the two machines is

equal, and since they are geared together the speed and core-losses are also equal. The assumption is made that the gear and friction losses are the same for both machines. Let R be the resistance of one armature in ohms.

The following readings are necessary :—

V_l = line volts.
V_m = volts across motor terminals.
V_g = volts across generator terminals.
I_m = motor current.
I_g = generator current.

Then total power taken from line $= V_l \times I_m$ watts.
„ „ output of generator $= V_g \times I_g$ „
„ „ losses in the two machines $= V_l I_m - V_g I_g$
copper loss in motor armature $= I_m^2 R$
„ „ „ generator „ $= I_g^2 R$

Subtracting the two copper losses from the total losses will leave the total core, field copper and friction losses, half of which will be the losses for one motor, i e :—

$$\tfrac{1}{2}(V_l I_m - V_g I_g - I_m^2 R - I_g^2 R) = L$$

Add to this the copper loss of the motor armature and the sum will be the total losses of the motor, i.e. :—

$$L + I_m^2 R = T$$

The output of the motor = input — total losses

$$= V_l I_m - T$$

Therefore efficiency of the motor per cent.

$$= \frac{\text{output}}{\text{input}} = \frac{V_l I_m - T}{V_l I_m} \times 100.$$

The Hopkinson or Back-to-Back Method. The Hopkinson method of loading back the generator electrically on to the motor and supplying only the losses of the set from the line is a more elegant method of testing and has the advantage of being much less wasteful of energy. Fig 56 shows the connections for this, the operation being as follows :—

(1) Start up the motor from the line by means of a starting rheostat. The generator is loaded on a rheostat to prevent the motor speeding up dangerously Finally short-circuit the starting rheostat.

(2) Adjust the voltage of the generator by means of the load booster until it equals the line voltage, i e. until $V_2 = V_1$

(3) Close the paralleling switch, P.

(4) Gradually reduce load on the load rheostat. The load

thrown off the rheostat will now pass through the two fields and motor armature and current can be kept steady by means of the load booster. Finally pull out load rheostat switch, L.

(5) Adjust the generator current on the load booster, and keep it so, taking care of line voltage fluctuations by means of the line booster.

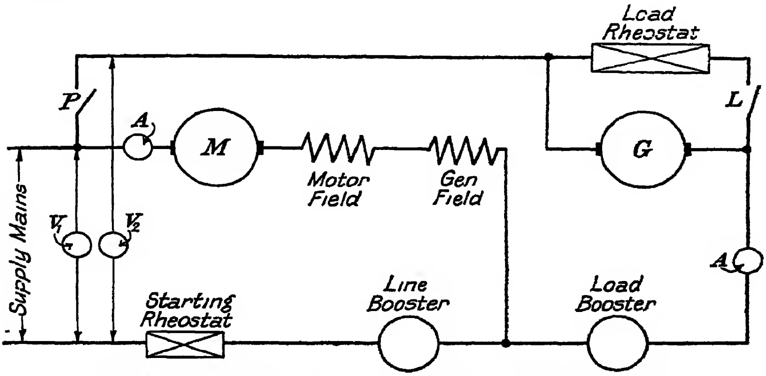


Fig. 56—Hopkinson Test on Two D C. Series Motors.

G. Hughes' Method. Mr. G. Hughes* used at Horwich works (L. & Y.R.) a method of loading back for two 1,200-volt motors from the 400-volt supply. It will be seen that the supply mains are made to act as a booster and supply only the losses. The need for high voltage switch gear is removed and no load rheostat is required since the low supply voltage (400 volts) will not allow the set to race. The motors are mechanically coupled as before and the diagram of connections is shown in Fig 57. Fig 58 shows the distribution of voltages The set is started up on the rheostat R_M with the generator field not excited, the generator field is then switched on and the load regulated.

Then combined efficiency of the set

$$= \frac{\text{generator output}}{\text{input from line} + \text{input to generator field}}$$

$$= \frac{V_G A_M}{\{(V_M + V_G) A_M + V_F A_F\}}$$

and efficiency of one machine and its gear

$$= \sqrt{\frac{V_G A_M}{\{(V_M + V_G) A_M + V_F A_F\}}}$$

* Hughes on "The Electrical and Mechanical Equipment of All-Metal Cars." *Proc. I.C.E.*, Vol. CCVIII, p. 226.

This is an approximation only, for since the excitation of the generator field is lower than that of the motor field, the iron losses of the former will be lower.

The method is a useful one for railway engineers who wish to

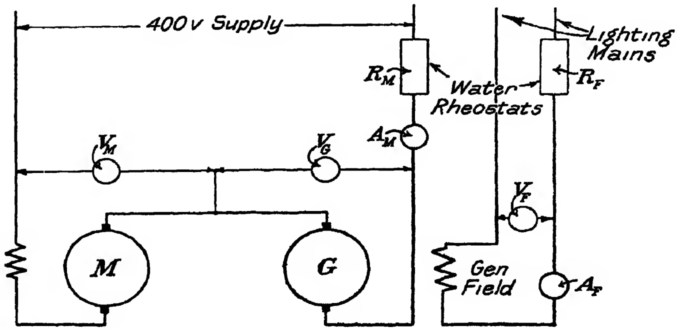


FIG. 57.—Mr. Hughes' Hopkinson Test on Two 1,200-volt Motors from 400-volt supply.

be able to make occasional full load runs for heating or other tests with a minimum of apparatus.

It could obviously be modified if preferred by using a booster set instead of the mains, and thus starting up and running without requiring a starting resistance at all. The booster must then

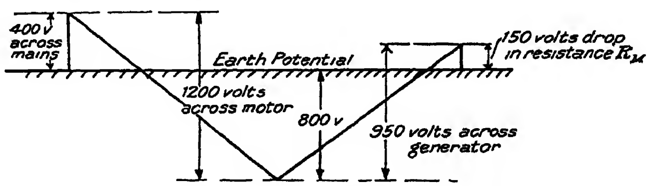


FIG 58.—Distribution of Voltages, Fig. 57.

be able to carry full load current and generate this current at a voltage such that its K.W. capacity equals the sum of the total losses of both machines. A very satisfactory booster could be obtained by using a third traction motor, fitting a pulley over its pinion and belt driving it from line shafting.

If any of these tests are made by gearing two motors through their pinions or by clamping the pinions together, the efficiency obtained will not include for gear friction.

It should be stated that in the above diagrams on motor testing the interpoles have been omitted for simplicity. Actually the interpoles must be left in series with the armature in each case, only the main field being ever reversed and separately excited.

CHAPTER VII

CURRENT COLLECTION

The supply of electric power to an electric train involves two distinct elements; the stationary element, and the moving element fixed on the car. The stationary element can take two distinct forms; the overhead wire which is suspended above the track, and the conductor rail which is fixed to the sleepers a few inches higher than the running rails. The car element is necessarily different in each case—for overhead wires the car element takes the form of the trolley pole, bow or pantograph, while for conductor rail systems some kind of shoe is employed. In all cases the engineering problem is that of maintaining continuous contact between the moving and fixed elements in spite of vibration, oscillation and other running conditions. Since the car element must be designed to suit the requirements created by the stationary element, it will be convenient to deal firstly with this latter.

Overhead Conductor Systems

The simplest form of overhead conductor system is that used on tramways, consisting of a continuous contact wire or "trolley wire," as it is often called in American parlance, suspended at intervals from insulators either from brackets carried on poles or from wires stretched across poles fixed at the side of the track. For railway work this has three disadvantages:—

(*a*) The sag caused by the weight of the wire;

(*b*) The short spacing permissible and hence the large number of suspension poles, which involves high cost and tends to obscure the driver's view of the signals;

(*c*) The points of suspension are rigid spots in an otherwise flexible wire and cause sparking, especially at high speeds.

To avoid these disadvantages and to enable an overhead trolley wire to be used satisfactorily for railway work, the catenary form of suspension was used (Latin: *catena*—a chain),

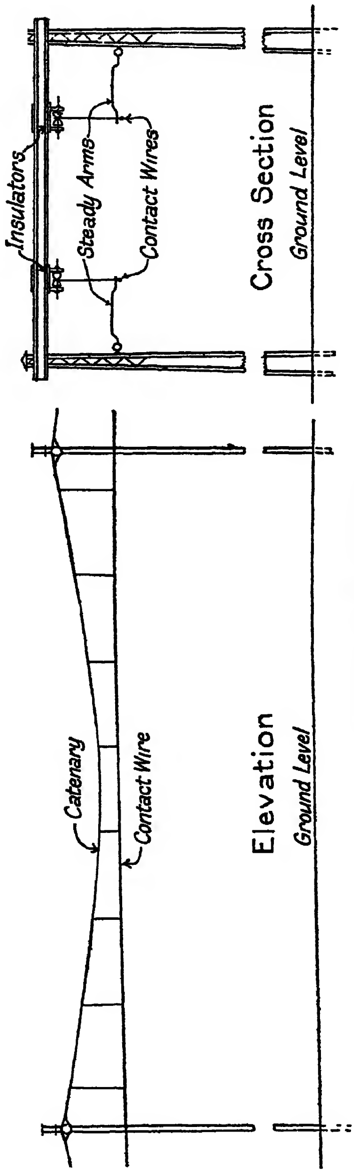


FIG. 59.—Single Catenary.

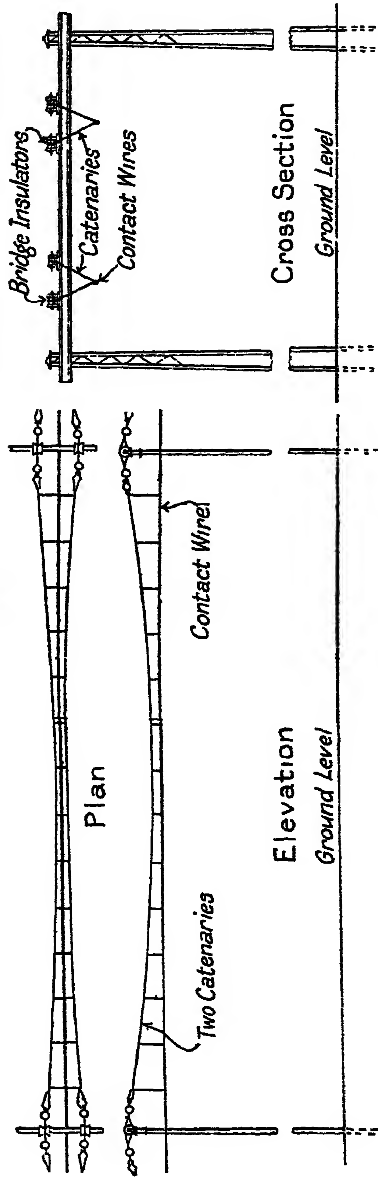


FIG. 60.—Double Catenary.

which in its simplest form (Fig. 59) consists in suspending the contact wire by means of clips or hangers of gradually varying length placed a few feet apart and hung from a "messenger" wire. The messenger wire hangs freely in a catenary curve from the main supports, and the whole arrangement is akin in principle to a suspension bridge. This simple arrangement is known as the *Single Catenary*, and is extensively used. Such simplicity, however, was not reached without difficulties In the early days of overhead working, and notably in the case of the Woodlawn-Stamford section of the New York, New Haven and Hartford Railroad, a single phase, 11,000-volt 25 cycles electrification comprising 22 miles of 4-track road, the engineers concerned set out to design in 1906 a form of overhead construction which should be strong enough to resist the effect of wind pressure, the weight of ice and snow, and to maintain a level horizontal contact surface in spite of expansion due to changes in temperature. It was feared that the single catenary would be insufficiently strong laterally to resist wind, and this was the main reason which led this railroad to adopt the *Double Catenary*. In this arrangement two main catenary wires are used, supported by and insulated from the track structures. They are tied together at frequent intervals by horizontal tie pieces of such length that normally the plane of each catenary is inclined to that of the other, the two planes forming a V in section. The trolley wire is attached to the catenaries by droppers of equal length so that it hangs centrally between the two catenaries, and in any cross-section of this arrangement the three wires are therefore at the corners of an isosceles or equilateral triangle, as shown in Fig. 60.

The advantages of this construction are that since the planes of the catenaries are given an initial inclination to the vertical plane, a very slight movement of the construction to either side of the track produces a powerful unbalanced force tending to prevent this movement; and that if one catenary were to break, the other would prevent the arrangement collapsing. The disadvantages are that three wires are employed, which is expensive in first cost and maintenance, and the success of the design depends largely on how the tie bars and droppers are arranged. In the original New Haven electrification, rigid tubular droppers were employed, the whole construction practically amounting to a triangular girder, and it was found that the points where the contact wire was clipped to these droppers formed relatively rigid spots—"hard spots"—in the otherwise

flexible trolley wire, causing pronounced arcing and wear at high speeds.

To remedy this a 4/0 grooved contact wire, originally of steel but afterwards of phono-electric material, was clipped on close below the original copper trolley wire, $1\frac{3}{4}$ in. centre to centre, the resulting additional flexibility proving necessary for the success of this construction. The triangular hangers are spaced 10 ft apart as are the clips supporting the phono-electric wire, but the latter are located midway between the main hangers to provide the maximum flexibility The main messenger cables are of $\frac{9}{16}$ in. diameter, made up of seven strands of extra high tensile steel. The spacing of supports is 300 ft, and the vertical sag in the middle of a span is 66 ins.

In 1907, or about the same time as the original New Haven construction was proceeding, the London, Brighton & South Coast Railway was electrifying part of its local lines on the single-phase 25 cycles, 6,700-volts system. Sir Philip Dawson, who was the consulting engineer for this work, succeeded in avoiding the "hard spots" by using light wires for horizontal tie pieces and droppers, the longer droppers being divided into two lengths linked together In this construction, which is shown in Fig. 61, the inertia added to the trolley wire is far less than in the case of the N.Y.N H. & Hartford Railroad and a 7/0 S.W.G grooved copper trolley wire is still being used successfully, practically no modifications having proved necessary. (The span used is 180 ft. to 210 ft.) Fig. 62 shows the parts in detail.

The double catenary construction was thus the pioneer system for main line overhead construction As experience was gained, however, it became evident that the wind effect could be provided against without using two main catenary cables, and a single catenary began to be developed instead. This has been so successful that the double catenary may now be considered as obsolete for new constructions.

The Compound Catenary. In the earlier single catenaries developed on the Continent, and especially in Germany, an auxiliary catenary was used, as shown in Fig. 63 This wire, usually of 0·05 sq in sectional area of solid steel, is supported at intervals from the main catenary and the trolley wire is hung from it in turn at about double as many points, thus increasing its rigidity against wind and helping to produce a level trolley wire. It will be seen from the method of suspension that the uniform level of the trolley wire is unaffected by expansion of

the auxiliary catenary wire, but is affected by that of the main catenary cable, and by that of the trolley wire itself

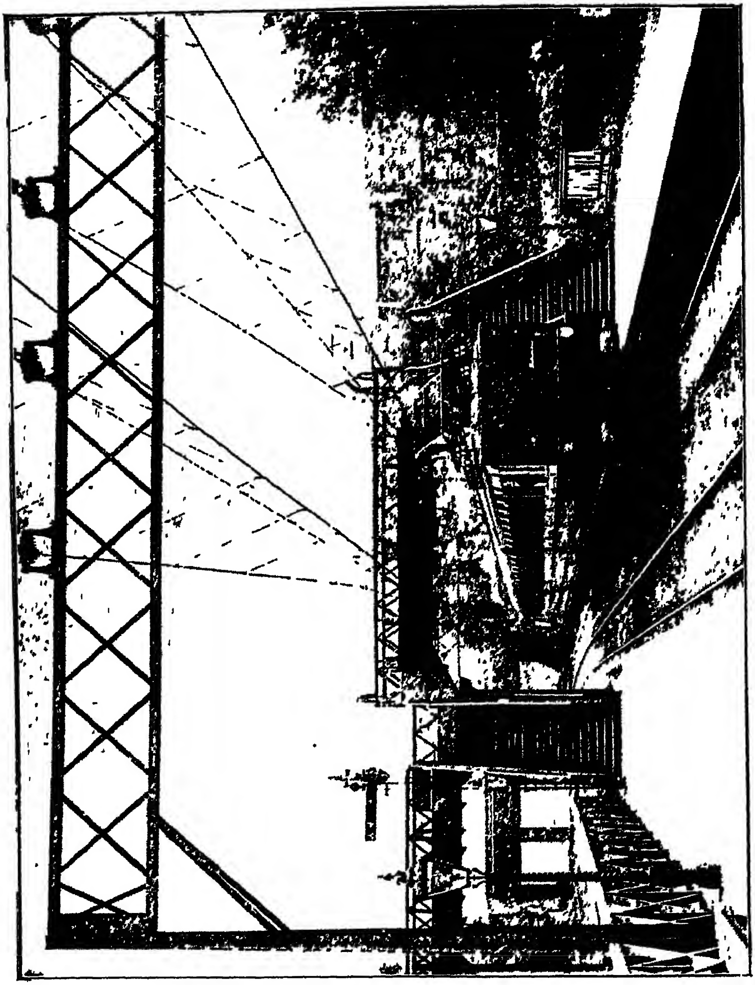


FIG. 61.—Double Catenary (L B & S C R.)

Two English examples of this so-called Compound Catenary construction may be quoted The Newport–Shildon line of the North-Eastern Railway, operating at 1,500 volts direct current, was partly in service in 1915 and uses a stranded main catenary

or messenger cable and solid steel auxiliary catenary. The trolley wires are double, two grooved copper wires being used each of ·155 sq in. section, attached to the auxiliary catenary by sliding clips. The normal span is 330 ft.—a greater span than has ever been regularly used before.

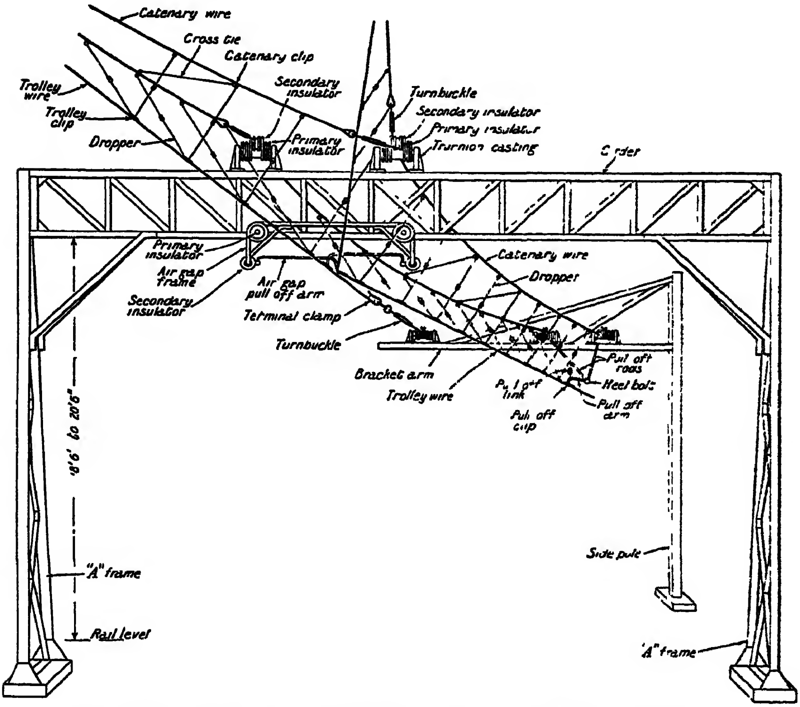


FIG 62.—Overhead Equipment; name of parts, London, Brighton & South Coast Railway.

Distance between standards, 50 ft. to 210 ft
Distance between trunnions, 2 ft 6 in to 7 ft
Distance between droppers, 10 ft
Size of trolley wire, 7/0 S W G
Size of Catenary Wire, galvanised steel, 12/13 S W G
Size of dropper wire, galvanised steel, 6 S W G
Strain on trolley wire, 18 cwt at 60° F
Breaking strain of trolley wire, 22 tons.
Elastic limit of trolley wire, 19 tons.
Weight per yard of trolley wire, 2 26 lb.
Stagger of trolley wire, 9 in from centre (original).
Stagger of trolley wire, 12 in from centre (existing).
Size of pull-off rods, ¾ in. steam tube.

The Morecambe–Lancaster section of the Midland Railway, a short experimental line of length equivalent to 21 miles of single track, operates on 6,000 volts, single phase The main catenary consists of two 7/16 S W G. steel cables, clipped

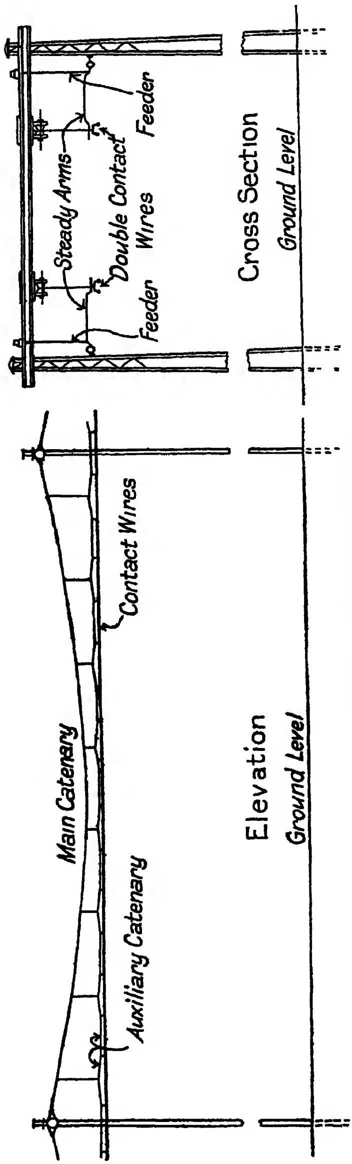


FIG. 63.—Compound Catenary.

together except where passing over insulators at bridges. The auxiliary catenary is a 7/13 S.W.G. cable, and a 3/0 S W.G grooved copper trolley wire is used. This is a typical Siemens-Schukert type of construction, of which many examples are found in Europe.

The Single Catenary. Experience showed that the auxiliary catenary was not really necessary and could be dispensed with, which was being done on some of the latest works in Germany before 1914. The single catenary is by far the simplest of all overhead systems and it finds much favour in Germany, France, U S.A , England and Australia The Bury–Holcombe Brook section of the L Y.R , a direct current 3,750-volt system, uses single catenary suspension, with normal spans of 150 ft. and 6/0 S.W.G. copper trolley wire.

The extensive Melbourne Electrification employs single catenary construction and the Sydney Electrification, due to open in 1926, will also use a single catenary, as does also the Midi Railway (France). The main line electrification of the Chicago, Milwaukee and St Paul Railroad, by far the most extensive electrification in the world, uses a single catenary construction on its 647 miles of single track, operating at 3,000 volts direct current. Perhaps the most

significant example is the latest work of the N.Y.N H. & H R R, the pioneers of double catenary construction, whose

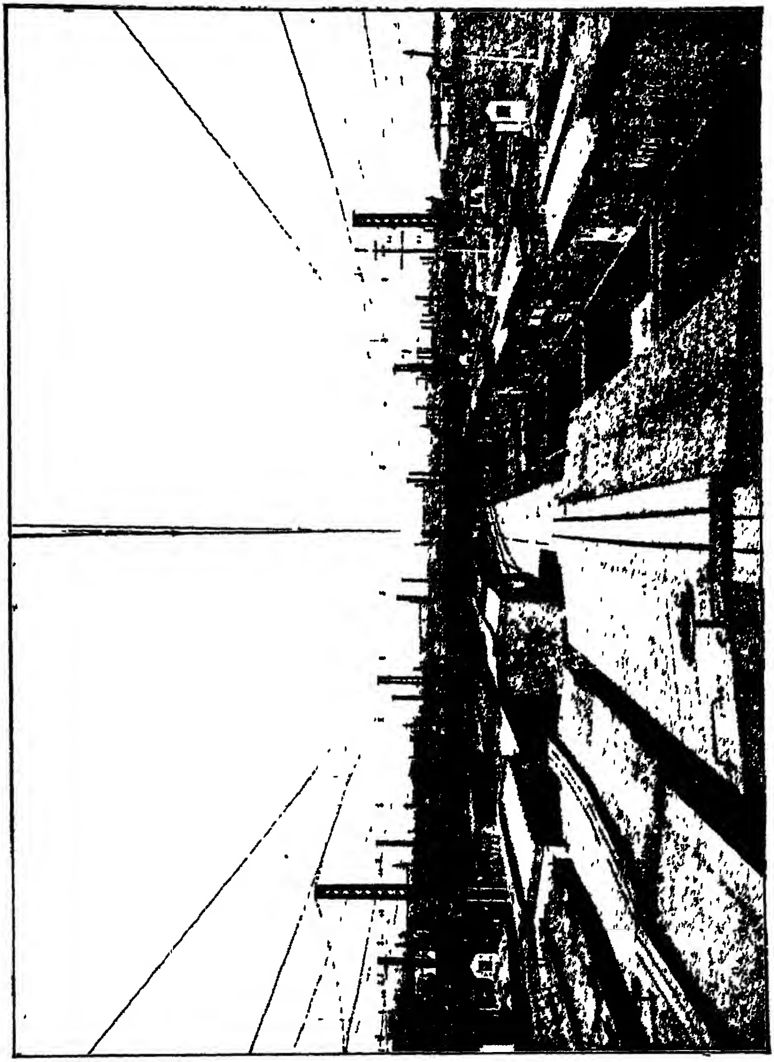


Fig. 64.—Oak Point Yard; New York, New Haven & Hartford Railroad.

development has been through the compound catenary to the single, an example of which is shown in Fig. 64.

Trolley Wires. Trolley wires are almost universally of hard-drawn copper or a bronze alloy known as "phono-electric" wire. The following composition of phono-electric wire has been found by actual analysis of a large number of samples .—

Copper	98·35 per cent.
Lead	Trace
Tin	1·33 ,, ,,
Iron . . .	0·14 ,, ,,
Balance, probably oxygen.	0·18 ,, ,,

Phono-electric material is much harder than copper but has 2·3 times its resistance, i e. about 40 per cent. the conductivity of copper. For high voltage A C. work, where the current collected is small, the resistance may be unimportant and the better wearing qualities may give phono-electric the preference. For tramway work it resists the wear of arcing better and as distances and current used are much less than on railways it finds much favour for tramway work. Its greater resistance to corrosion is a recommendation where steam locomotives pass over electrified tracks, but in spite of these features the greater conductivity of copper usually causes that material to be preferred for railways, especially for direct current work. The properties of the two are compared in the following table :—

B & S Gauge	Area of grooved Wire sq in	Area of same gauge Wire without Groove sq in	Weight in lbs per 1,000 ft		Resistance Ohms per 1,000 ft at 20°C.		Breaking Load lbs	
			Hard Copper	Phono Electric	Hard Copper	Phono Electric	Hard Copper.	Phono Electric
3/0	1314	1318	508	508	0636	·1494	6,700	9,100
4/0	1665	1662	641	641	0504	·1182	8,125	11,450

The elastic limit for both materials is 75 per cent. of its ultimate strength. The area of the same gauge wire without grooves is shown for comparison in the third column, showing that the grooved wire is of larger diameter than the same gauge number round wire, but of almost exactly the same cross section.

Round section wire was first used for trolley wiring but the clips form projections which are particularly undesirable on curves. A "figure 8" section was then used, the top part of the 8 being held by the clip while the lower and larger part

formed the wearing depth. This section, which was never standardised, is unsymmetrical and presents considerable difficulties, such as twisting during installation, and the grooved section has now become universal practice. Fig. 65 shows two of the three American Standard Grooved Sections, the third standard being the 2/0 B. & S (Brown and Sharp) which is more suitable for tramway use. It may be mentioned that a 4/0 B. & S. is often written thus :—0000 B. & S , also that areas of wire are often expressed in "Circular Mils," this expression being the

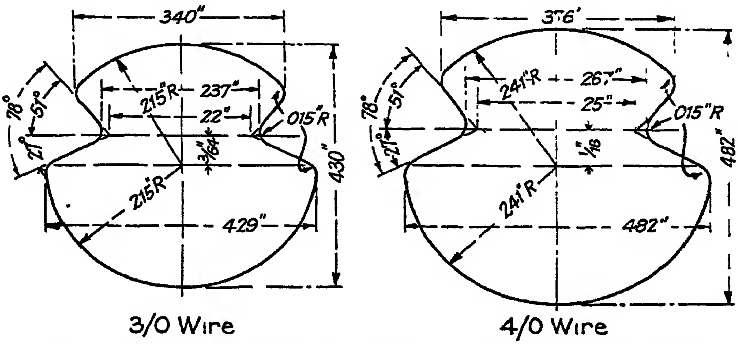


FIG 65 —American Standard Grooved Trolley Wire Sections

diameter in mils squared. (1 mil = one-thousandth of an inch) Thus the area of a wire 0·036 in diameter is 36 × 36 = 1,296 circular mils ; the factor $\frac{\pi}{4}$, which would give the area in square mils, being omitted.

Double Trolley Wire. In certain D.C. electrifications, where heavy currents have to be collected, a double trolley wire has been used to enable the pantograph to make contact with two wires in parallel. The Chicago, Milwaukee & St Paul and the Newport–Shildon lines are examples of this, but in view of the results obtained with modern pantographs on an extremely flexible line, it appears likely that all the current collection needed can be obtained from one wire and it seems doubtful whether engineers will use two trolley wires in future electrifications.

In Fig. 63 both wires are suspended from one clip and are uniform in height, while in other instances greater flexibility has been aimed at by supporting the trolley wires from alternate

droppers as shown in Fig. 66. It has been found that the two wires show a current-collecting capacity of 1·8 times that of one wire.

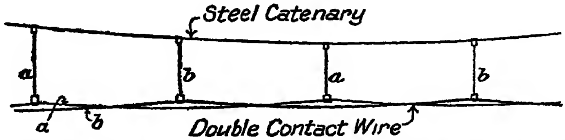


FIG. 66.—Double Trolley Wire, Alternative Arrangement Method of Supporting two Contact Wires by Alternate Droppers.

Wear of Trolley Wire. The Chicago, Milwaukee & St. Paul line, with twin 4/0 B. & S. hard copper trolley wires and 30 lbs. pantograph pressure, showed an average wear of ·011 in. and a maximum of 02 in after five years, during which time 43,150 pantographs had passed the section, the average current collected being 1,000 amperes at 3,000 volts This result shows that the working life of trolley wires is likely to be very long indeed. The experience of the L B. & S.C R. is that the wear at any point is directly proportional to the total quantity of current collected at that point

Leakage. The L.B & S C.R. on 70 miles of single track at 6,700 volts have found an average leakage of about 20 B.T Units per hour, which presumably includes the normal dielectric losses of the insulators.

Catenary Cable. Catenaries may be of steel or bronze. Nearly all the double catenary construction used is on single-phase lines and stranded steel is generally used for the main cables. These cables are often connected in parallel with the trolley wire to increase the current-carrying capacity of the system, but the proportion of current they carry is small and the resultant heating effect is inconsiderable. Further, since the expansion co-efficient of steel is only 65 per cent. of that of copper, the expansion of steel cables is not great, even over an extreme range of temperature. The effect of a given amount of expansion in increasing the sag of a catenary depends on the initial sag, and by erecting a steel catenary with a sag of about 2½ per cent. of its span a stranded steel cable of small section can be used with a high safety factor, while the additional sag at the centre over an extreme range of temperature can be kept within practical limits.

A steel catenary has therefore the advantage of mechanical

strength and immunity from temperature effects, but is liable to corrosion, for which reason it is standard practice to galvanise it. On the L B. & S C R , where steam trains run over electrified tracks, the whole of the catenaries and metal fittings are now dipped into hot tar for two hours before erection, since experience has shown that the renewals of catenaries and droppers in sections where there is no steam traffic is only one-tenth of what it is in sections where a large amount of steam traffic is running.

For single-phase lines steel is the best material to use for catenaries since the relatively greater immunity from corrosion possessed by copper or phono-electric material has not appeared to be a sufficient reason for the use of these materials in place of steel for single-phase working, where even a small trolley wire will carry all the current required For direct current working, however, the conditions are different by reason of the lesser voltage, and the overhead system must possess high electrical conductivity, often equal to as much as 0·5 sq. in. of copper for each track, and it is evidently a great advantage if the catenary can be used to carry current and so avoid the need for feeder cables running in parallel with it along the track.

On a section of the Newport–Shildon line and the whole of the Melbourne system, the construction is entirely non-ferrous, and full electrical and mechanical use is made of all copper present. The Melbourne system uses a catenary of hard-drawn stranded copper cable of ·25 sq in. section, with a trolley wire of ·25 sq. in. section, and no other feeders are required.

Tensioning of Wires. The temperature effect caused by weather changes or by the carrying of current produces effects both in the trolley and catenary which tend to upset the true alignment of the trolley wire. Automatic tensioning of the catenary by means of weights and pulleys has been attempted on the Continent but does not appear to have been successful, and the tendency is towards its abandonment. Automatic tensioning of the trolley wire has been employed on many railways, though opinions are divided as to its efficacy. It is common practice on the Continent, but unusual in the United States, possibly on account of the flexible supporting structures which include many wooden pole supports, and although it is installed in Melbourne it does not appear to be really necessary for Australian conditions

The Newport–Shildon line uses tensioning structures made of strong steel masts, braced and fitted with two cross girders

with a centre strut. The tensioning weights are slung in the centre of the mast structures by chains passing over pulleys attached to the contact wires, and by this means a normal tension of about one ton is maintained in the double contact wire.

Stagger of Trolley Wire. To prevent the wear caused by rubbing on the trolley wire from taking place at one point on the contact shoe of the pantograph or bow collector it is usual to " stagger " the trolley wire, i e to arrange it to cross and recross the centre line of the track. Such an arrangement is shown in plan view in Fig. 67

About 12 ins. stagger each side of the centre line is usually allowed, and the L B. & S.C R. have adopted this amount in place of the 9 ins. originally provided. The amount of relative

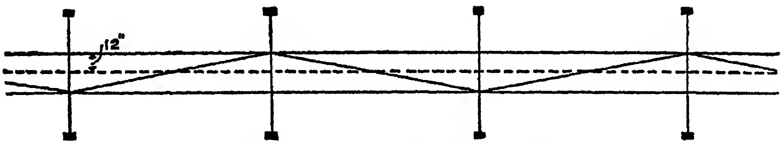


FIG. 67.—Stagger of Trolley Wire.

lateral movement between the collector and trolley wire caused by the natural rolling of the train must be taken into account in considering the amount of stagger necessary, and some lines have not adopted a staggered wire

Erie Current Collection Tests. Mention may be made of a series of tests carried out at Erie by the American General Electric Company in July, 1923. The suspension system is a new type of compound catenary in which a primary steel messenger cable is suspended on steel bridges spaced 300 ft. apart. The secondary messenger, a stranded copper cable, hangs from the primary by droppers spaced 15 ft. apart and from it the twin 4/0 grooved hard copper trolley wires are supported by clips spaced 15 ft. apart on each wire. The trolley wire is ideally flexibly suspended, the inclined lacing allowing it to lie with its own weight on the pantograph Currents of 5,000 amps at 1,500 volts were collected by a standard pantograph at about 60 m p.h. with an entire absence of sparking. The normal pressure of the pantograph on the wire was 30–35 lbs.

The line thus arranged was a short experimental track only and has not been developed for regular use, but the results suggest that there is almost no limit to the amount of

current which a pantograph can collect from a well-designed line

Three-Phase Overhead Construction. For three-phase work two overhead lines are necessary, the track being used as the third phase The two overheads must be suspended to be well clear of each other and of structures and also of the current collectors of the other phase. This involves shorter spans and frequent anchoring of the trolley wire to prevent lateral displacement and naturally complicates the special work at cross-overs and junctions owing to the crossing over of wires of different phases. Nevertheless the Italian State Railways, which operate at about 3,300 volts with bow collectors, have made a decided success of their system, whose installation was a daring innovation at a time when the single-phase motor had not been developed for traction work and high voltage direct current had not been thought of.

Conductor Rail Systems

In low voltage direct current railway systems the power is usually supplied to the trains from an insulated steel conductor rail, placed parallel to the track a short distance outside the track rails. This rail, which forms the positive side of the electrical system and is known as the "third rail," is of special chemical composition (*see* p 150) to give high electrical conductivity and the rail joints are "bonded" with copper bonds to provide electrical continuity. The track rails are themselves similarly bonded and connected in parallel with each other to form the negative earth return of the system.

In some cases, notably in and around London, e g the Metropolitan, District and Tube Railways, the L. & N.W.R. and North London Railways, an insulated negative called a "fourth rail" is used. The advantages and disadvantages of a fourth rail are discussed later in this chapter.

The conductor rail may be of the top contact, under contact, or side contact types, each of which may be protected, i.e. insulated against accidental contact with passengers or linesmen; or unprotected.

Top Contact System. The top contact rail is universally used for low voltage (600 volts) working in England. The London Tubes use a rail of almost rectangular section as shown in Fig. 68 The flat-bottomed Vignoles pattern rail is used by the L & N.W.R. and the L. & S.W.R. and others, as shown

in Figs 69 and 70, while an inverted channel section is used on the Central London Railway and the Hammersmith & City Railway (Fig. 71.)

The lengths of conductor rail rest by their own weight upon porcelain or composition insulators which are secured by two clips screwed by coach screws to the sleepers (Fig. 72). The rail is thus generally free to take the slight movements caused by the passage of a heavy train, without which flexibility there would be tensile and bending stresses imposed on the insulators which would cause breakage. At about every fourth insulator the rail is "anchored," i.e fastened by a bolt passing through the web of the rail to a clip which locks its position on the insulator while still allowing for general flexibility and for thermal expansion. Sometimes the anchoring is made to a

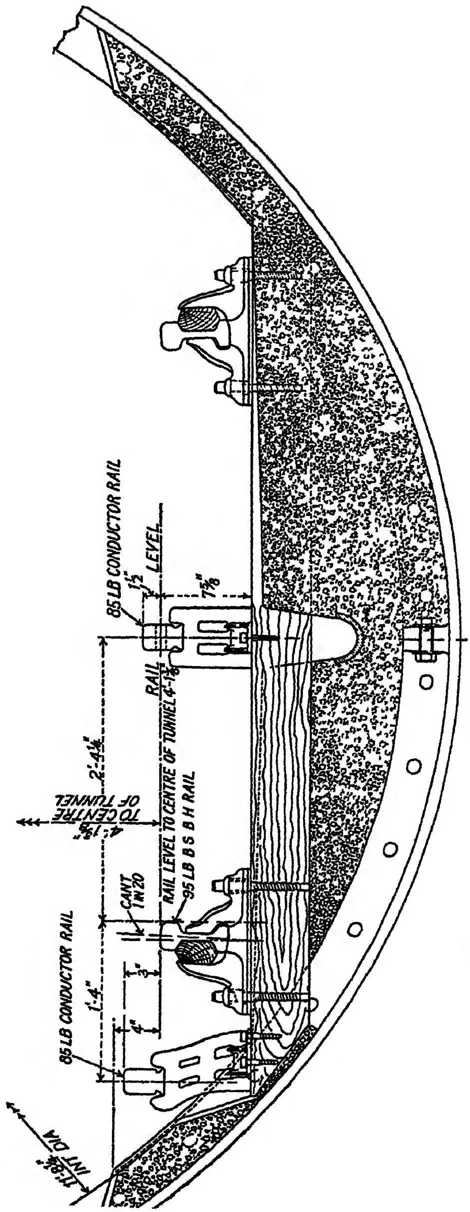


FIG. 68.—Permanent Way and Conductor Rails, London Tube Railways.

concrete post embedded in the ground The system shown in Fig 73 is used by the L. & N W.R. and L. & S.W. Railways The position of the third and fourth rails was standardised for British practice at a meeting held at the Railway Clearing House, Euston, in March, 1903, when it was agreed that the face of the third rail should be 3 in and that of the fourth rail 1½ in. above the track rails, and this has been generally adhered to since passenger and goods rolling stock of all railways may at any time have to pass over a portion of electrified line The lower

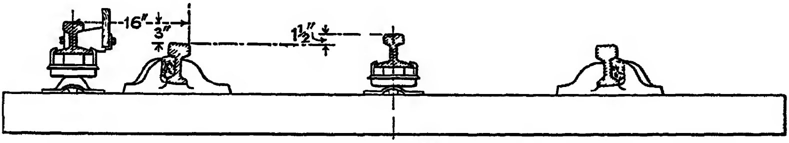


FIG 69.—Cross Section of Track, Metropolitan District Railway.

FIG 70.—Cross Section of Electrified Track, L. & S.W.R.

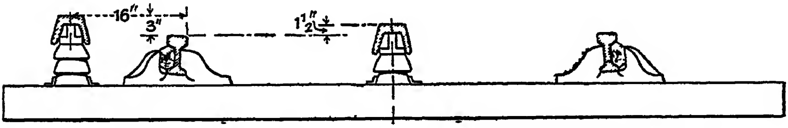


FIG. 71.—Cross Section of Track, Hammersmith & City Railway.

level of the fourth rail was adopted to avoid the possibility of hanging coupling chains of goods wagons fouling the rail. It is necessary, however, to keep it above the track rails to enable the collector shoes to ride over a crossing without touching the track rails. At the same meeting it was agreed that the horizontal distance between the centre of the track and that of the third rail should be 3 ft 11½ in, but this has been somewhat departed from in the London area.

In the case of the Lancashire & Yorkshire 600-volt lines (Fig 74) the middle rail is not a contact rail but a steel conductor bonded to the two track rails to provide additional carrying

capacity for the uninsulated return path. Any single length of fourth rail or track rail can therefore be taken out for repairs without affecting the current to trains in the next section.

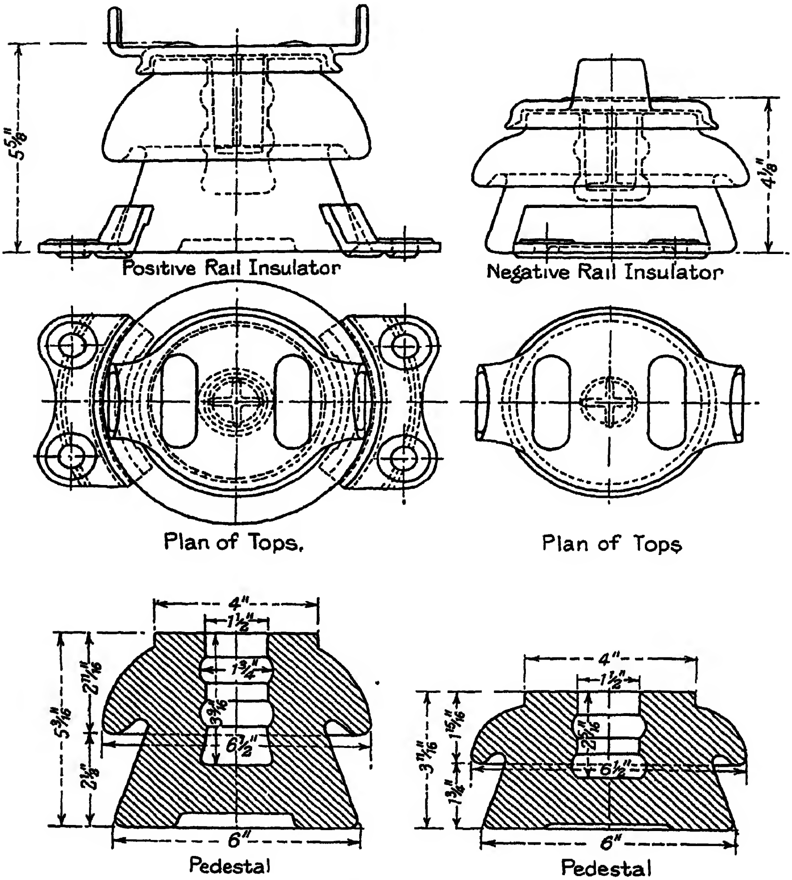


FIG. 72—Conductor Rail Insulators

In American practice a copper cable is preferred for the purpose in cases where the return circuit needs reinforcement.

The top contact rail and collector shoe gear is extremely simple to instal and maintain, but it is difficult to protect the rail from accidental contact with persons walking on the line or

with the picks and shovels of permanent way men. There is also trouble from the brake pins of goods wagons which often

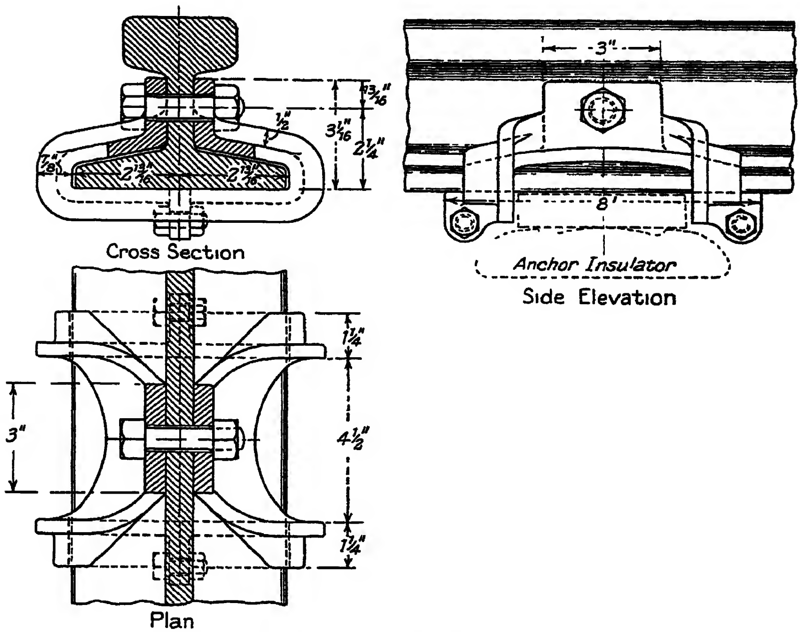


FIG 73.—Conductor Rail and Clip for Anchor Insulators.

hang down and make contact with it. Further it is very subject to trouble from snow, and a sudden frost following sleet will

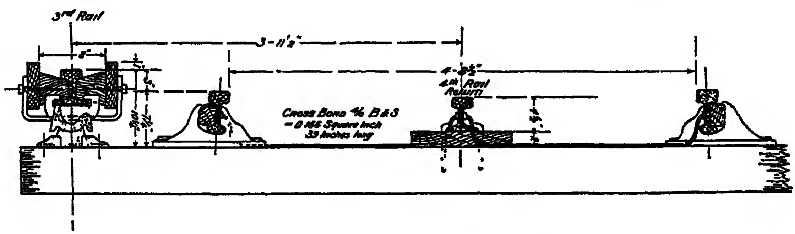


FIG. 74—Cross Section of Electrified Track, Liverpool–Southport Line, L.Y.R.

often produce a thin film of hard ice on its surface which entirely prevents the shoe from collecting current and has often com-

pletely paralysed the train service. Various sleet-brushes, scrapers and sleet-cutting shoes fitted with inserted cutters have been tried, and the L. & N W.R. has tried a jet of steam followed by scrapers and wipers, but none of these methods can be considered entirely successful for removing ice.

Under Contact Systems. The under contact rail offers greatly improved protection against accidental contact of all kinds and from sleet and ice. Fig 75 shows the New York Central Railroad protected third rail which has the advantage of using a standard section of bull-head rail with considerable allowance for wear The system is very satisfactory, and although

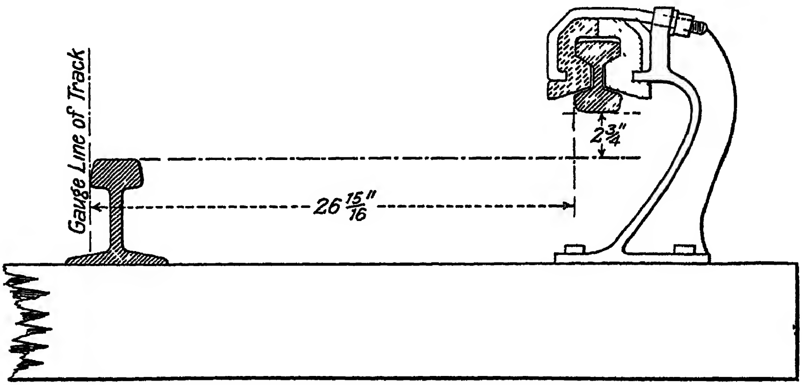


FIG. 75—Under Contact Conductor Rail, New York Central Railroad.

the insulators are held in tension and shear they do not appear to give much trouble. This design is quite unsuitable for English conditions, as is clearly shown in Fig. 76. This diagram shows a cross-section of the L. & Y. R. track (Liverpool–Southport line) with the New York Central rail shown dotted upon it. It will be seen that it is quite impossible to place this under contact rail to avoid fouling the rolling stock if placed in the space between the rails and the platform or between the two track rails, and if placed farther out, as in American practice, immense alterations to bridge girders and platforms would be required.

Fig 77 shows the design of rail successfully used on the Central Argentine Railway, in which a rail section of very special type is required. This gives the advantage of support from

below, and hence allows of much less overall height than the New York Central design

Fig 78 shows a new type of under-contact rail developed

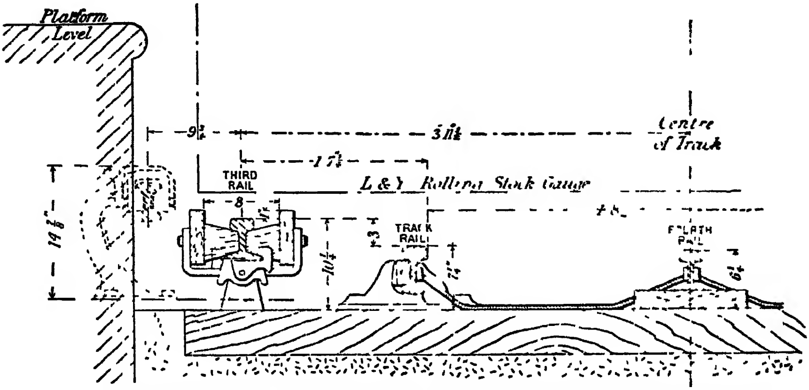


FIG 76—Cross Section of Permanent Way of Lancashire & Yorkshire Railway, showing Third and Fourth Rails compared with New York Central Railroad

Dotted lines show position of protected third rail as used by the New York Central Railroad, and illustrate how this position for the third rail would be in the way of the platforms and certain bridge girders on an English railway.

after a study of the Central Argentine and United States operation It is intended for 1,500-volt working A C-shaped

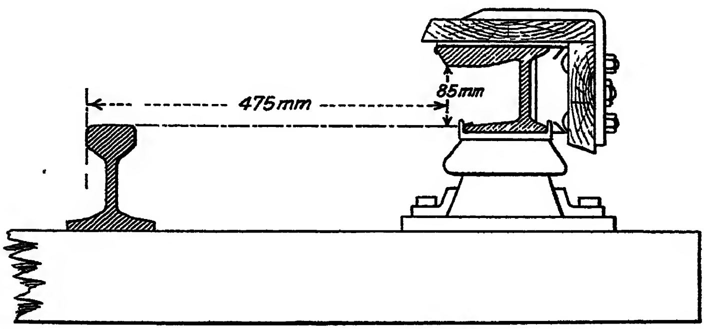


FIG. 77—Under Contact Conductor Rail, Central Argentine Railway.

bracket, mounted on an insulator, supports the U-shaped conductor rail over which is hung the insulation in the form of

an inverted trough. The conductor rail weighs about 100 lbs. per yard and allows for a considerable amount of wear. It is so balanced that when simply laid on the brackets it maintains its position by its own weight, the centre of gravity being below the plane of support and the weight is far greater than the upward pressure of the shoes. Single fish-plates are used with countersunk bolts for joining the rail lengths. The protective

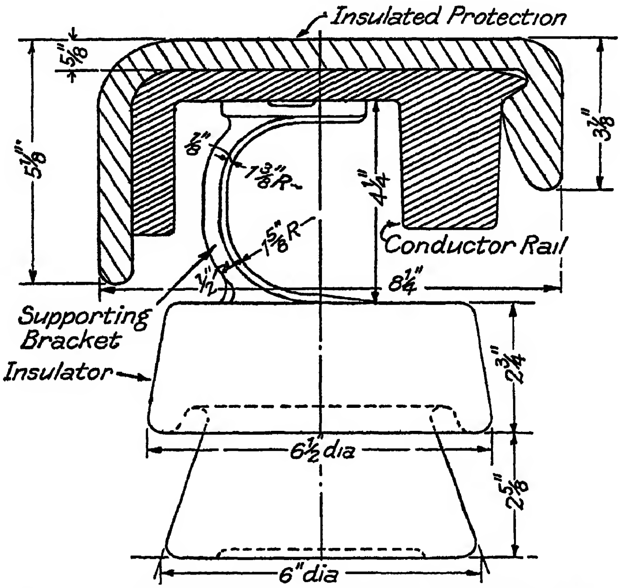


FIG. 78—1,500-Volt Under Contact Conductor Rail.

covering is of moulded non-inflammable composition supplied in 6-ft lengths which permits of straight lengths being used on most curves It is simply slipped over the rail and snapped into place, being then self-locking. Each length laps over the adjacent length Successful tests on this rail are reported as having been conducted on the London, Midland & Scottish Railway with speeds up to 70 miles per hour, and it will be interesting to see whether it is largely adopted in future.

Side Contact System. The side contact rail shown in Fig. 86 later in the chapter was developed by Sir John Aspinall for the later (Manchester–Bury) section of the Lancashire & Yorkshire Railway, operating at 1,200 volts, and has proved

extremely successful in use, combining some of the advantages of both the other types of rail. Its protection is excellent, it conforms to the requirements of the structure and rolling stock gauges and it appears to suffer little inconvenience from ice and from snow except when the snow is deep

Rail Bonding. To maintain electrical continuity for the large currents used, often 2,000 amps. at starting, it is necessary to bond the rails The bonds used are of copper, divided into strands and suitably shaped to allow of the expansion of the

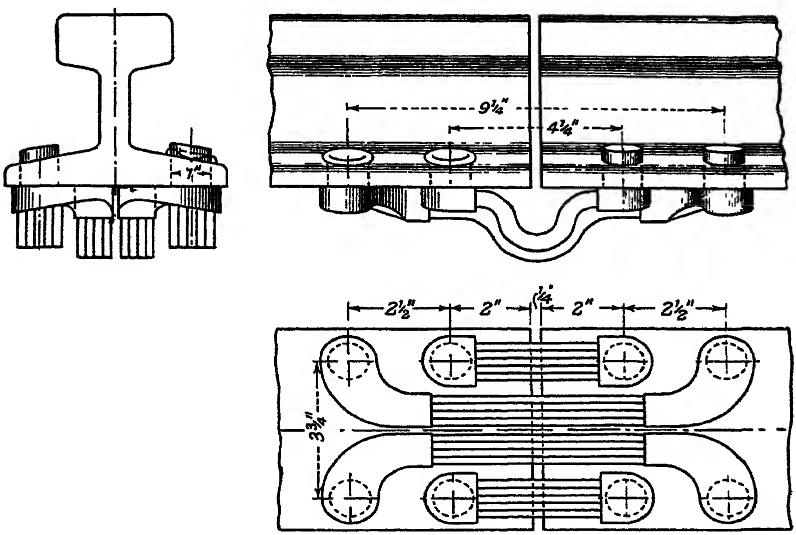


FIG. 79.—L N.W R and L.S.W.R. Rail Bond.

rails A great number of bonds in English practice have been fitted by drilling the rail flange or web, inserting the bond and squeezing it out with a portable hydraulic jack. Fig 79 illustrates this, but the present trend of practice is to use oxy-acetylene or electric welding for the purpose. The cross-section of the bonds should be decided from a consideration of the density of traffic carried, and some representative figures are given below. Conductor rails are made in as great lengths as possible (about 60 ft.) to reduce the number of bonds. Sir John Aspinall quotes the following figures for the Liverpool–Southport line .—

Resistance of 1 mile of bonded 3rd rail, 70 lbs per yard, 6·84 sq. ins section . . .	0 0425 ohm.
Ratio of resistance of 1 ft of solid rail to 1 ft of rail containing a joint bonded with new bonds	1 to 1·57
Ratio with all web bond strands cut . .	1 to 2·4
„ „ „ strands cut except 6 . .	1 to 7·26
„ „ „ strands cut, fish plates only .	1 to 1182

The last three values illustrate the value of good maintenance of bonding

The following leakage test made on the Bakerloo Tube Railway may be of interest :—

Length of track tested, miles	3·47
Volts between positive and negative	575
Volts between positive rail and earth . . .	520
Volts between negative rail and earth	50
Leakage, positive to negative, amperes . . .	0 68
Leakage, per mile of single track, amperes . . .	0·196
Leakage, positive rail earthed, amperes. . . .	6·75
Leakage, negative rail earthed, amperes . . .	0·74

Points and Crossings. The track work at points and crossings is usually spoken of as "special work" Such places necessitate a break in the conductor rail and a "jumper" cable connection is made between the two ends In many cases this cable is allowed to lie on the surface of the track or it may be taken below ground. The latter is a neater job, though much more expensive to instal or replace, and the cable is entirely protected from weather The ends of the rail are bent downwards to provide a "ramp" for the contact shoe to ride up without shock on striking the rail after a cross over. The L & N W.R. use a special cast steel leading ramp and a shorter trailing ramp instead of bending the rail. At turn-outs a double splayed-out ramp is required to accommodate the contact shoes of trains either passing straight over or turning-out, since otherwise the side of the shoe would strike the rail. This is shown in the frontispiece The side ramp on the positive rail has in later extensions been avoided by depressing the positive rail at this point. At such special work, where a rail is interrupted it is usual to place a short length of conductor rail on the opposite side of the track to prevent an interruption of the circuit, collector shoes being provided on both sides of the car for the purpose.

Sometimes the amount of special track work makes it impos-

sible to preserve continuous contact for locomotives which have no trolley bus line and a length of overhead rail has to be provided, special collectors being provided on the roof of the locomotive to collect current from it

The table on next page shows the chemical composition of some representative conductor rail steels The steel is always of low carbon content and is soft, so that it rusts much more readily than track rail steel Its life is much more affected by rusting than by wear and it is therefore advisable to keep the conductor rails well painted, but the difficulty of getting really satisfactory paint often results in this not being done.

Overhead Current Collecting Gear

The overhead conductor is carried normally at a fairly uniform height above the track, but this height has often to be reduced considerably to enable the wire to pass under bridges, through tunnels and the like, and the collector gear has therefore to be designed to maintain continuous contact with the wire over a considerable range of height, sometimes between about 17 ft and 25 ft, and to maintain as nearly as possible a uniform upward pressure throughout that range The trolley wire may be displaced from the centre of the track at certain places to avoid fouling structures, at curves and for other reasons In all these cases the collector gear must be able to follow closely the changes of height, and as it must also be able to follow small irregularities without arcing it must evidently possess flexibility combined with lightness, i e absence of inertia These are the main essential requirements for which collectors have to be designed.

Trolley Wheel Collector. This is familiar in tramway work and is much used on inter-urban railways in the U S.A , but is little used for railway work in the English sense of the word, though it still survives in the slow speed 3-phase locomotives used in the Cascade Tunnel of the Great Northern Railway of U S A The use of the trolley wheel collector necessitates mechanical continuity of the overhead wire at all crossings, turn-outs and the like, and when track points are set over, the points of the overhead wire must be set over to correspond, as may be seen in tramway systems of the same kind. At high speeds considerable damage can be caused to the overhead work before the driver is aware that one or more of his trolleys have left the wire, and the disadvantages of this form of collector are very evident.

CHEMICAL COMPOSITION AND RESISTANCE OF CONDUCTOR RAILS.

Railway.	Impurities.					Resistivity	
	Carbon.	Manganese.	Phosphorus	Silicon	Sulphur	Ratio of Specific Resistance of Rail to Specific Resistance of Copper at 20° C	Specific Resistance
	per cent	per cent	per cent	per cent	per cent		Microhms per inch cube
North-Eastern	0.05	0.4	0.1	0.2	0.08	7.25	4.93
Lancashire & Yorkshire (600-volt lines) . . .	0.045	0.23	0.046	Trace	0.04	7.23	4.91
Lancashire & Yorkshire (1,200-volt lines)	0.08	0.22	0.034	0.022	0.026	6.75	4.6
Metropolitan District (London)	0.035	0.315	0.056	Nil	0.059	6.5	4.42
London & North-Western* . .	0.044	0.139	0.011	0.03	0.029	6.5	4.42
London & South-Western . .	0.047	0.34	0.053	Trace	0.055	6.75	4.6
Central London	0.03	0.33	0.052	Trace	0.045	7.5†	5.1
	0.05	0.19	0.05	0.03	0.05	6.4‡	4.35
London Electric (tube) Railways	0.05	0.19	0.05	0.03	0.05	6.4	4.35
New York Subway (U.S.A.)	0.10	0.60	0.10	Nil	0.05	8.0	—
Interborough Rapid Transit Co (U.S.A.)	0.161	0.561	0.091	Trace	0.055	8.56	—

* This conductor rail contains 0.255 per cent nickel

† Original conductor rail

‡ Conductor rail used for extensions and renewals.

The Rolling Cylinder. This, as used on the Butte, Anaconda & Pacific Railway, and the Oakland Division of the Southern Pacific Railway (both in California), avoids some of the objections to the trolley wheel in that its use removes the need for moving parts in the overhead wiring The cylinder, however, has to be made comparatively short and the supports for the trolley wire require to be nearer together than is the case with other systems in order to limit the amount of side displacement caused by wind. The upward pressure on the wire is about 48 lbs. In the example quoted, the cylinder is mounted on a pantograph framework and can revolve in either direction. The cylinder has necessarily a considerable inertia which is undesirable, the roller complete, inclusive of bearings, weighing about 31 lbs , and a great deal of trouble with the bearings has been experienced, especially at high speeds, and some form of sliding collector is therefore becoming standard practice for railway work.

The sliding collector takes two distinct forms, the " bow " and the " pantograph," the operating principle being somewhat different in the two cases.

The Bow Collector. This consists, in its simplest form, of a light metal bow making contact with the trolley wire and inclined at a trailing angle in the same way as the arm of the trolley wheel collector Contact is maintained by spring pressure, and the whole collector is made very light so that it can follow the irregularities of the overhead wire and track without sparking. The bow collector is much used on the Continent of Europe and was adopted on the Heysham–Morecambe single-phase section of the Midland Railway, and on the London, Brighton & South Coast Railway In the L.B. & S.C. Railway, working at 6,700 volts, the height of the trolley wire varies from 13 ft. 9 in to 20 ft , with gradients of 1 in 75, and the collectors have been in use since about 1911. The bow-strip is of aluminium and has a life of 2,000 to 3,000 miles. The upward pressure is 12 lbs at the normal height and varies from 13·5 lbs to 10·5 lbs. within the range of height stated. Roller bearings are fitted. A disadvantage of the bow collector is that it is suitable for operation in one direction only and therefore two bows must be provided. The springs of the L.B. & S.C bows are actuated by compressed air pressure. On arrival at a terminal station the motor-man throws his reversers by the reverse handle of the master controller. When the reverser

has thrown, its interlocks actuate automatically the air valve to the air cylinders, bringing down the bow which has been in use and erecting the other ready for running in the reverse direction. One bow touches the trolley wire before the other leaves it, thus avoiding sparking during the change over. This bow can be seen in Fig. 61.

The Pantograph Collector. This is now practically standard practice all over the world. The sliding collector is carried on a jointed framework of light steel tubing called a pantograph from its general resemblance to the linked magnifying and reducing drawing-office instrument of that name Pantographs may be divided into three classes :—

1. Spring raised, mechanically lowered.
2. Spring raised, air lowered.
3. Air raised, gravity lowered.

In the first of these, the pantograph is held erected by a number of spiral springs, operating through flexible chains to bell-crank levers on shafts which can rotate through a half turn. The bell-cranks are in effect cams and are shaped spirally, so that as the shaft rotates the lessening pull of the spiral tension springs is compensated for by acting at a greater radius from the axis of the shaft and so producing a practically uniform upward pressure on the trolley wire throughout the working range of height. (The "fusee" of an English clock employs the same principle for the same purpose, i e. of maintaining a uniform torque with a gradual reduction of spring pressure) The curvature is often modified slightly to allow the collector to begin to rise quickly from the down position.

Modern pantographs are usually fitted with two pans of sheet steel about 5 ins wide fixed by pin hinges to the top of the diamond-shaped framework. Each pan contains two rows of renewable wearing contact strips, fixed with a space between the two rows which is filled with a lubricant, often a mixture of petroleum jelly and graphite Lubrication reduces wear and "singing" noise and appears to reduce chattering and the resultant sparking. The pans are flexibly hinged to the pantograph frame by means of two small spiral springs in compression, which allow the pans individually to tilt in either direction independently of the pantograph frame, thus providing a contact of low inertia for taking up the small irregularities without sparking, the pantograph frame accommodating the larger changes of height. The total upward pressure on the trolley wire for either a single or double pan pantograph is usually about 25 lbs.,

but adjustment is provided for tightening up the springs and thus increasing the pressure if required, the range being about 15 lbs to 35 lbs. The operation of the pantograph is to raise the trolley wire slightly while passing under it When running at high speeds the pantograph is subjected to considerable stresses which it must be strongly built to withstand; the swaying of the locomotive or coach is transmitted to a contact 8 ft above the roof at considerable leverage, and the same is true of the blows received at crossovers or wherever the trolley wire is interrupted. The slope of the trolley wire when passing under bridges should not be too steep, preferably not more than a 1 per cent slope. If the upward pressure on the wire is normally 12 lbs it may require 17 to 20 lbs pressure to force the pantograph down slowly, owing to friction, while the extra inertia effect at high speed is evidently considerable when it is considered that a speed of 60 m p h. on a 1 per cent slope represents a rate of pushing down of the pantograph of over 10 ins. per second This down speed is proportional to the train speed and the inertia effect increases as the square of the downward speed, so that for high speed working a gentle slope of the trolley wire is imperative.

The joints of the pantograph are fitted with enclosed grease-filled ball or roller bearings to reduce friction and are electrically shunted by means of flexible copper braid The whole of the pantograph is built up on a rectangular angle-iron frame which is carried on the roof and insulated therefrom by porcelain insulators at each of the four corners. The main cable carrying the current is connected to any part of the framework of the pantograph.

The pantograph is pulled down when required by an insulated rope until the side frames pass a spring catch which locks it in the down position. An auxiliary rope releases the two side catches simultaneously and allows the springs to bring the pantograph into the erect position. A ratchet and pulley system is sometimes used, especially if it is desired to raise and lower from the driver's cab in cases where the pantograph is fixed at the trailing end of the car

The advantage of this spring operated pantograph is its simplicity; there are no air cylinders, valves or train wires and little to give trouble On the other hand, the various pantographs of a train must be raised and lowered individually by hand, which is less of an objection on a locomotive than on a long multiple-unit train. Remote-controlled pneumatic opera-

tion allows the driver to raise or lower all pantographs simultaneously by power, a faculty which is often of use in coasting over a section of damaged trolley wire

Spring Raised, Air Lowered Pantographs. The arrangement of pans, contact strips and framework generally is nearly identical with the simple type just described The piston rod of an air cylinder is connected so that its force causes a rotation of the main shafts of the framework with a consequent lowering of the pantograph The piston rod continues its travel beyond the dead centre so that in its extreme position the pantograph is mechanically locked down. To erect it again, air is admitted into a second cylinder, the first being now allowed to exhaust to atmosphere, and the piston of the first forced back, allowing the springs to raise the pantograph Admission of air into the cylinders is controlled by two small valves, fixed in the driver's compartment, solenoid-operated and remote-controlled by a two-position switch in the driver's compartment. Two control wires are thus required throughout the train for operating all pantographs simultaneously, and a handle is provided on the electro-pneumatic valve for the release of individual pantographs if desired There is a small storage reservoir which can be charged with air and then isolated for operating the pantograph, when there is no air in the main reservoir. A hand pump is also provided for raising the pantograph when the train has been standing long enough for all air to have leaked out of the pipes and reservoirs. The pistons are usually packed with cup leathers and are made single acting. Since double-acting cylinders would involve stuffing-boxes and packing, which is undesirable, two cylinders at least, and sometimes four, are provided. The whole air mechanism is mounted on the main framework and is therefore normally at line potential, necessitating a rubber hose or other insulated connection to the air pipe.

Air Raised, Gravity Lowered Pantographs. This type differs from the last described in the reversal of function of the springs and air engine. Two sets of springs are provided working against each other, the "lowering" normally overcoming the "raising," and keeping the pantograph in the down position On the admission of air to the cylinders the lowering springs are compressed, thus allowing the raising springs to erect the pantograph, so that although air pressure is the prime force causing erection, the actual raising is done by the springs, and the resilience of the springs is available for taking up irregularities in service. The two electro-pneumatic valves, two control

wires and hand pump are required as in the air-lowered type In lowering, air is exhausted from the cylinders and the pantograph collapses by gravity, the tension springs become extended as it falls and soften the impact, while a restriction of the exhaust valve of the air cylinders produces a dash-pot effect for the same purpose To prevent air leakage, a catch can be fitted which locks the pantograph in the erect position and allows air to be cut off from the cylinders, but the saving does not appear to justify the complication of the lock and air valve to release it

In all air-operated pantographs, the air supply to the cylinders is usually taken through a reducing valve from the main reservoir pipe of the brake system, the cylinder pressure being 50 to 70 lbs. per sq in The air is supplied from the main reservoir pipe and not from the brake pipe, whose pressure is reduced when the brakes are applied A small reservoir is supplied and connected to the pantograph air pipe by a three-way cock, so that the reservoir can be isolated after being fully charged. The other two positions of this cock are for raising the pantograph with the hand pump and for normal operation from the main pipe system If a pantograph has to be lowered for a few hours during shunting, a repair job or for any other purpose, there may still be pressure enough stored in its reservoir to raise it and so start the compressor, without having recourse to the hand pump The spring raised, air lowered type is now regarded as practically standard in America, while English manufacturers incline to favour the air raised type. Fig. 80 shows the latest Metropolitan-Vickers Company's standard pantograph in the erect position. Two cylinders are employed, and the weight complete as shown is 1,080 lbs. The frame is seen to be cross braced and joints are pinned and brazed into sockets.

In Continental practice, especially for very high voltage working, a combination of the pantograph frame and bow collector is often used, Fig. 83, the diamond frame providing the vertical adjustments and the bow replacing the pan. The bows are light and are spring supported and reversible as to direction. In other cases, Fig. 81, two such bows are used on one pantograph to increase the current collecting capacity. Fig. 82 shows a bow collector with two auxiliary bows. The bow collector strip is often made of aluminium for lightness, hardened by the addition of a small proportion of copper, but copper contacts have approximately double the current-carrying capacity of aluminium. Using a standard double slider pan

collector and a specially flexible overhead line, the General Electric Co of U.S A (*G E. Review*, September, 1923) has found no difficulty in collecting 5,000 amps from a single pantograph at speeds of about 60 miles per hour at 1,500 volts with a complete absence of sparking, and there appears to be no limit to the current-collecting capacity of the slider collector if properly designed. Pantographs are preferably placed over the trailing end of a coach to give the maximum distance between two collectors in case two motor coaches are coupled together

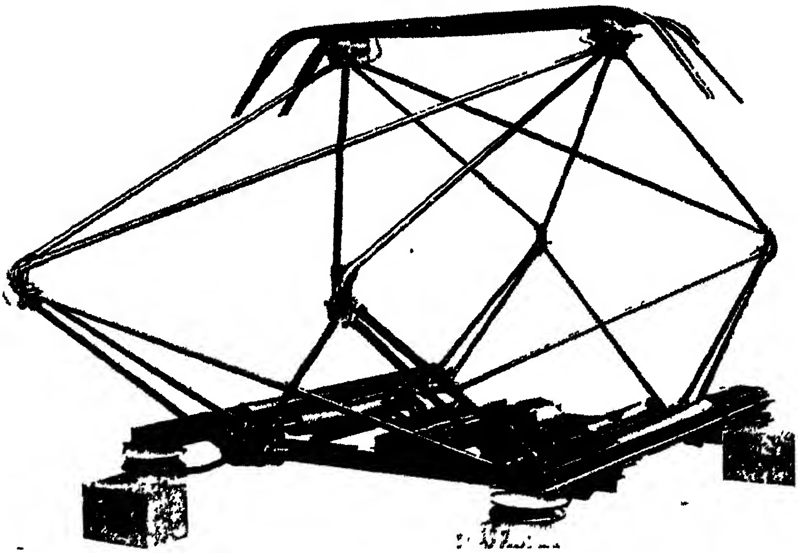


FIG 80 —Metropolitan Vickers Pantograph Erect

The ends of the pans are often extended into " horns " to prevent the overhead wire from getting caught under the collector shoe after excessive rolling or in other extreme positions, and to allow of picking up the trolley wire when entering from a cross over. In the " hornless " type of pantograph, which is less popular, the contact pans are made longer to avoid the need for horns which to be entirely satisfactory often require to be unduly long. The life of a pantograph contact strip may be given as about 6,000 miles.

Fig 84 shows the two bow collectors used on the Italian State Railway's three-phase system.

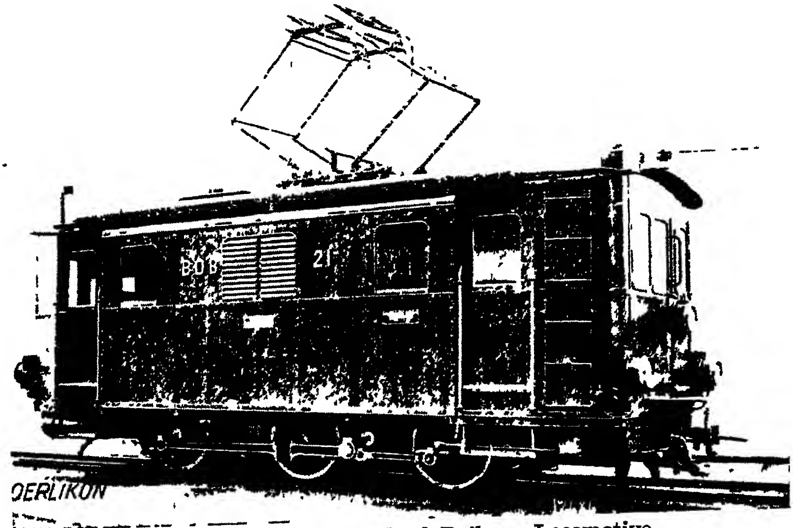


Fig. 81.—Bernese Oberland Railway Locomotive

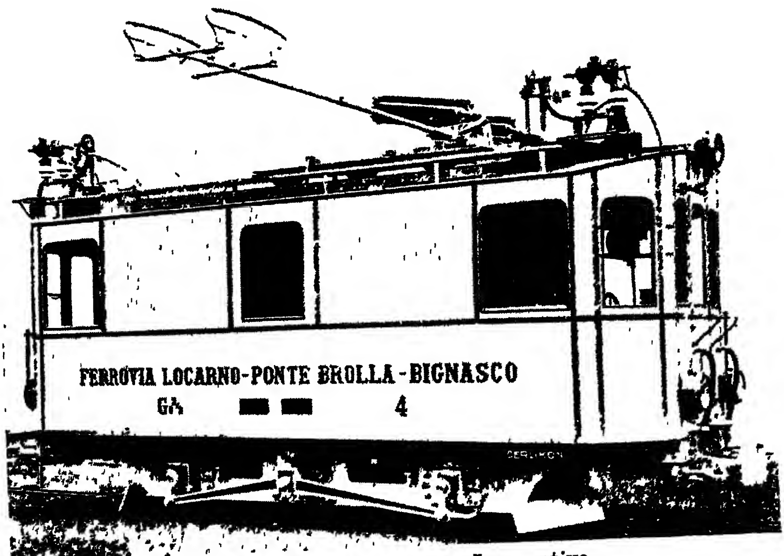


Fig. 82.—Light Railway Locomotive.

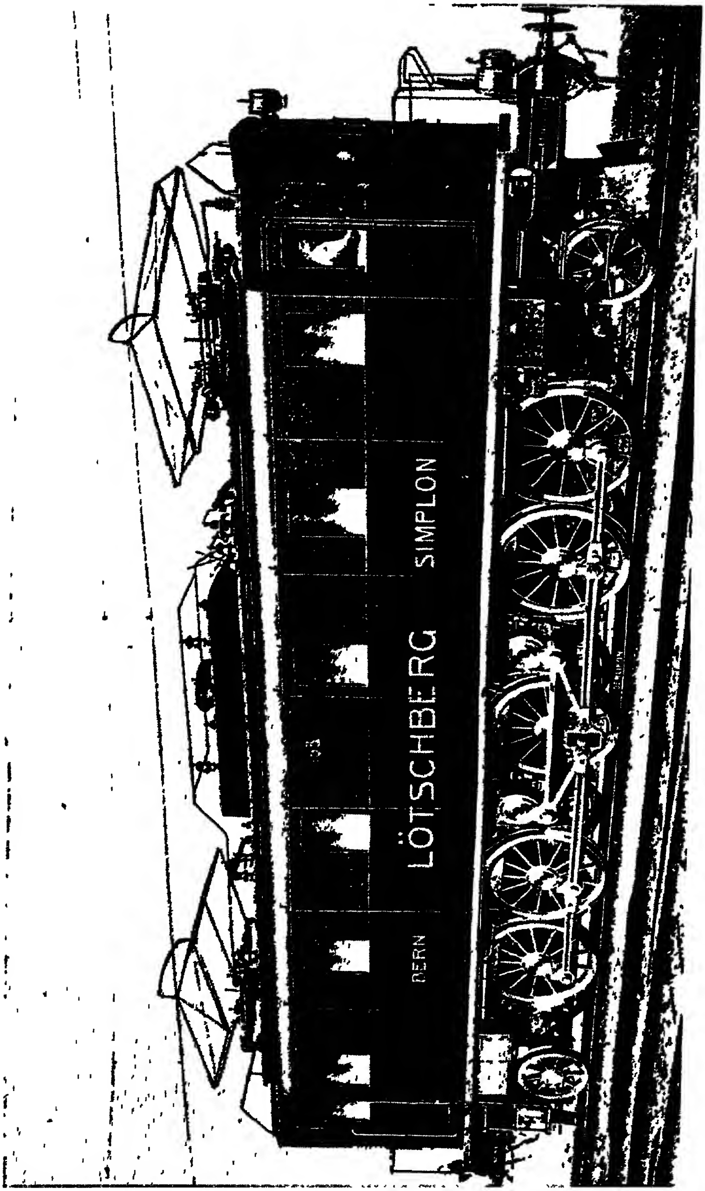


Fig 83.—Lotschberg Railway Locomotive

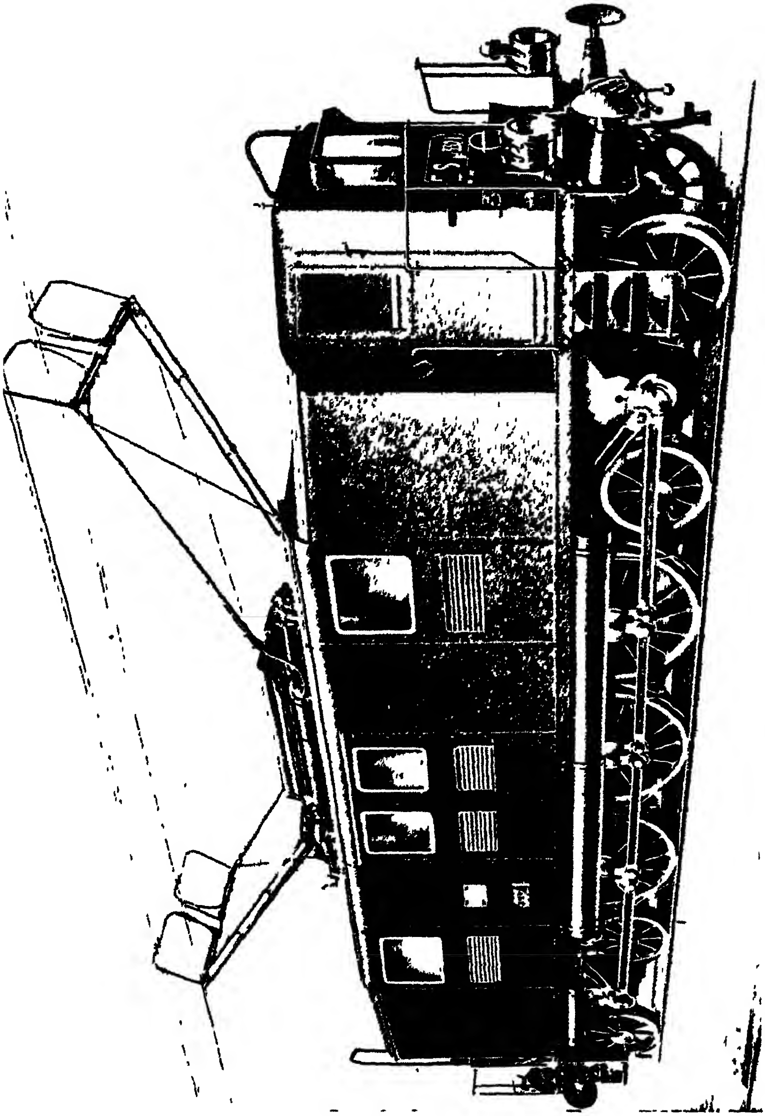


FIG. 84.—Italian State Railway Locomotive.

Conductor Rail Shoe Gear

Fig. 85 shows a design of top contact shoe gear in use on the L. & N.W R The positive bracket, which is a steel casting, is bolted to an oak or teak beam which is bolted to an extension of the axle boxes and is therefore not spring borne. The negative shoe bracket is exactly similar but is carried on a short beam bolted to a bracket fixed to the motor frame. The links are of cast iron and the slots, which are necessary to allow the shoe to ride up a ramp, also provide a weak spot or "mechanical

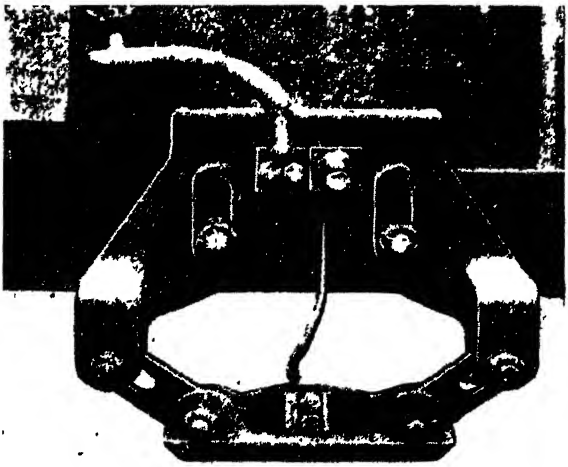


Fig 85.—Top Contact Shoe Gear (L & N.W.R).

fuse." Thus an obstruction on the track, which might otherwise strike a severe blow to the shoe gear of a train travelling at high speed and might break the shoe beam and possibly cause a derailment, merely snaps off the links and allows the train to pass. The shoe is of cast iron and is electrically connected to the bracket by a flexible copper braid of circular section Vertical adjustment is provided both up and down from a mid-position The lowest position of the shoe beam evidently occurs when the wheel treads and track rails are fully worn and the axle bearings worn down The maximum upward adjustment is evidently necessary when a new shoe is to be fitted to a bogie

maximum downward adjustment is required to allow a shoe to be completely worn out on a car whose wheels are new. The depth of shoe available for wear is $1\frac{1}{8}$ in , the shoe shown in Fig. 85 being half worn out. The shoe is set to hang freely about half an inch below the face of the conductor rail. The angle of inclination of the links, when the shoe is hanging freely, is about 30 degrees with the horizontal, which has proved to be the best angle for reducing sparking and appears to be standard practice The weight of the shoe itself, however, varies considerably on different railways: the L. & N.W R. shoe illustrated weighs 25 lbs. when new; the L. & S W.R. shoe about 70 lbs , and the London District Railway shoe 30 to 40 lbs.; the L & Y. (600-volt system) 64 lbs , while the Tube shoes are very light indeed All these shoes depend on gravity for their contact. In the under contact shoe used on the Central Argentine Railway, the upward pressure required is provided by two spiral springs, stops being used to limit the extreme positions of the shoe, both up and down. This type of shoe has also been developed for use with top contact rails with considerable success Fig. 86 illustrates the design of the Aspinall side contact shoe-gear

Comparison of Overhead and Conductor Rail Systems. For high voltage working, the insulation, danger to life and other difficulties render the conductor rail system unsuitable. The 1,350 volts of the L & Y. is the highest pressure in use on conductor rails at present An under contact system working on 2,400 volts was attempted by the Michigan United Railroad, but the breaking and sudden re-application of motor current occurring at ramps caused pressure surges and consequent burning out of motors, for which reason it was abandoned in favour of 1,200 volts.

Mr Raworth has made an interesting proposal to use a positive and negative rail with the track rail at earth potential, so that the track forms the middle wire of a 3-wire system, thus avoiding much of the insulation difficulties of high voltage working.

Alternating current traction would show few advantages unless a high line voltage were used, for which purpose the use of conductor rails is out of the question. No instance is recorded of an alternating current conductor rail system.

Conductor rails of rolled steel supported on insulators fixed to the sleepers evidently form an arrangement simple and cheap to instal and maintain, for the material costs are low and all

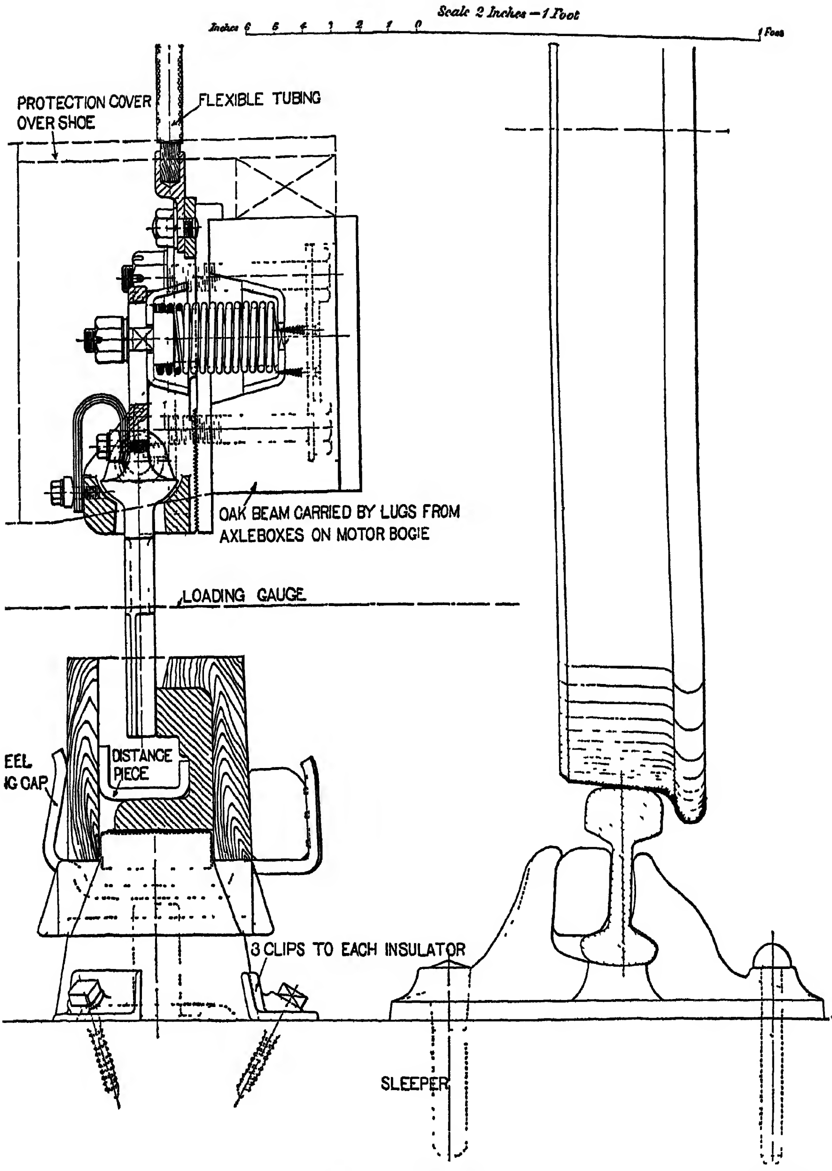


FIG. 86.—Side Contact System, Lancashire & Yorkshire Railway.

maintenance can be effected without the need for special cars with elevating platforms.

The objections to conductor rails are briefly as follows :—

(1) Greater danger to linesmen and passengers, especially at night. Owing to the number of accidents in Connecticut, U S A , the third rail system was banned by law.

(2) Less space in the track for walking, which is of importance in shunting work.

(3) A derailment disturbs the conductor rails, thus increasing the difficulty of restoring working conditions The short circuit caused renders imperative the use of a steam locomotive to bring up breakdown tackle

(4) Interruption to traffic caused by snow and ice. (Flooding with water does not cut off current to tracks)

(5) Cost of alterations to point rods and signal connections, and sometimes to water and gas mains.

(6) Long gaps in rails necessary at points, crossings, level crossings, etc.

The inductive effect of the third rail sometimes causes trouble with the sub-station machinery, and where this is the case the difficulty is avoided by running a bare copper cable inside the flange of the conductor rail, electrically welded to it at intervals. The result is that the copper carries the bulk of the current, while the rail takes the rubbing wear

In spite of all that can be said against it, however, the conductor rail system represents a sound mechanical and electrical job in cases where moderate voltages are employed, and many of the objections to its use appear more considerable on paper than in actual practice.

Three versus Four Rails. It will be appreciated that the insulated negative rail is a costly system to instal in the first case, but it avoids all troubles in the way of electrolytic corrosion and interference with earthed communication circuits, and imposes no limitation to the permissible voltage drop in the return rail. It puts no difficulties in the way of using the track rails for " track-circuit " signalling and there are no heavy bonds to make and unmake when renewing the track rails. In the case of a derailment, however, there is considerably more damage done to the track with two conductor rails than with one (rails being usually overturned and insulators smashed) and the maintenance of two sets of rails and of collector shoes in good working order and set at the correct height and alignment is evidently a more costly matter than is the case with an earthed return. In

shunting yards the fourth rail considerably restricts the walking space available. Where, however, a railway has to run trains over another line using a fourth rail, the fourth rail system is of necessity imposed on it, as in the case of some of the lines in the London district

Electrolysis. It is well known that in tramway working the return current through the track rails often finds a path of lesser resistance by leaking away through the earth to neighbouring gas and water mains, cable sheathing and the like, rejoining the track further on. The point at which the current leaves the buried conductor acts as an anode in an electrolytic cell and very serious corrosion is often produced For this reason the Board of Trade limits the permissible voltage drop in tramway rails in Great Britain to a maximum of 7 volts, and the fear of the same restriction seems to be present in the case of railways, though it has not been imposed. Railway tracks are carried on timber sleepers laid on a ballast of broken stones and are therefore much less effectively earthed than are tramway rails , further, the buried conductors liable to be damaged are generally further away from the track and the curves are less sharp. The corrosion is therefore much less than is experienced in tramway operation and is distributed over a greater surface. It is advisable to maintain the ballast well below the track rails, a precaution which has enabled the Paris suburban lines of the State Railway to prevent all electrolysis troubles.*

The maintenance of good bonding is the first essential to keeping the voltage drop of the third rail as low as possible, and, if a fourth insulated return rail is used, the danger is entirely eliminated.

For alternating current working, with an overhead wire and track return, the leakage currents are often larger but the electrolytic erosion is fortunately much less. In certain cases the insulating of pipe joints or bonding of pipes has to be resorted to, but such cases are fortunately rare.

* *Electrification of the State Railways, Paris and Suburban Lines.* A. N Mazen, Inst. of Elect. Engineers and Soc. des Electriciens. Paris, May, 1913.

CHAPTER VIII

SINGLE-PHASE RAILWAYS

Single-Phase Systems. In the early days of electric traction, before a suitable single-phase motor for traction purposes had been developed, it was predicted that a single-phase system would prove the only practicable one for main-line electrification, chiefly on account of the fact that power could be supplied at a high voltage to a trolley wire of small section and reduced to a lower voltage by means of transformers carried on the trains, thereby completely obviating the need for sub-stations. Although events have not entirely justified this prophecy, the simplicity of high-voltage distribution is the chief claim put forward on behalf of the single-phase system.

The single-phase induction motor has not found favour for traction work. It is inherently incapable of exerting a large torque at starting and cannot easily be arranged for variable speeds, so that it shares the disabilities of the continuous current shunt motor in being unsuitable for traction service, and a machine with series characteristics is therefore the objective aimed at by designers.

Since the direction of rotation of a direct current motor is always the same irrespective of the direction of the current with which it is supplied, it follows that ordinary D.C. motors can be used with single-phase alternating currents.

Before, however, the design of an actual single-phase motor is considered it will be well to consider two electromotive forces which are induced in an armature by an alternating field. Imagine an ordinary D C. armature made to revolve in an alternating flux as in Fig. 87, by being belt driven or coupled to a motor, no current being supplied to this armature. Now there will be two E M F.'s set up in the armature, the Rotational E.M.F. and the Transformer E.M.F.

The Rotational E.M.F. is the back E.M.F. with which we are familiar in D.C. machines, with the difference that the field

flux is now an alternating one. At any given instant, all the armature conductors on the left-hand side of the axis BB′ will be cutting the field flux in one direction and the E M F induced in them will be in the same direction. Similarly the conductors on the right-hand side of BB′ will all have an induced E.M.F of the same direction, but this direction will be opposite to that of the other side

Starting with zero potential at B′, all the E.M F.'s on the left-hand side add up to produce a maximum total potential at B. On the right-hand side, starting with zero potential at B all the E M.F 's add up to produce a maximum total potential at B′ of equal magnitude but opposite polarity to B. Conse-

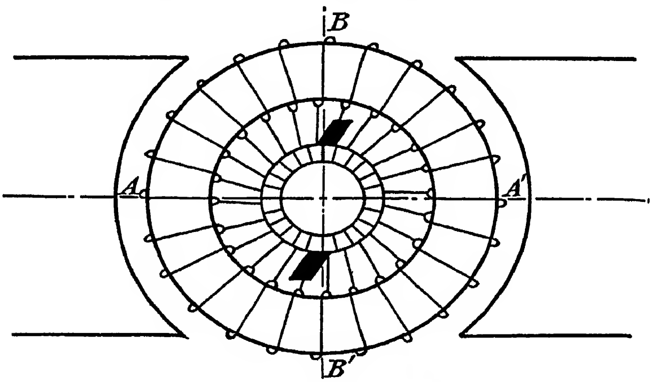


FIG. 87.—D C Armature revolving in A.C. Field.

quently the maximum difference of potential due to rotation is found between B and B′.

A reversal of the field will cause a reversal of this potential difference, and the frequency of this rotational E.M F. depends upon that of the field and is independent of the speed of the armature.

The magnitude of this voltage depends upon the speed of cutting lines of force by armature conductors and on the field strength, and is therefore proportional to armature speed. Being caused by cutting the lines of field flux, this rotational E M.F. is in phase with the field flux, i e. practically in phase with field current except for the lag due to hysteresis.

It should be noticed that although the individual conductors at A and A′ are those in which the highest E M.F. is induced, there is no difference of potential between them, and that the greatest difference of potential is between B and B′.

Transformer E.M.F. If the armature is now considered stationary, there is still a magnetic flux alternating through the armature core, which will therefore induce a voltage in the armature conductors which behave as the secondary of a transformer. The maximum transformer E M.F. will be induced in those conductors which lie in a direction at right angle to the flux (as in a transformer), which are those at B and B′. There will be no E.M F. generated at A and A′. But since the E.M F.'s in all conductors above the neutral axis AA′ will all be generated in one direction and those below AA′ in the opposite direction, it follows that sum total of the individual E M F 's will reach a maximum at A and A′, where they will be of equal value but of opposite polarity. Hence the transformer E M F. is a maximum between A and A′, which is an opposite effect to the rotational E M F.

The phase of this transformer voltage obeys the usual transformer law and lags 90 degrees behind the flux since it is proportional to the rate of change of flux which is a maximum at the zero value of flux Its frequency is evidently the same as that of the flux Its magnitude depends only on flux strength and the rate of its alternation and has the same value whether the armature rotates or is stationary.

Suppose now a D.C. series motor of usual design be supplied with single-phase current Owing to the pulsating torque caused by the alternating current there will be considerable vibration at starting, there will be heavy sparking and the high inductance of the motor will cause a lagging current and hence a low power factor. The most obvious improvement is to laminate the field and so reduce eddy currents in it.

We have now the following E M F.'s in the armature :—

(1) Rotational or back E.M.F , as has been fully described. Its phase will be the same as that of the main flux which is in phase with the main current and hence lags behind that of the supply voltage

(2) Transformer E M F as described, 90 degrees behind the current in phase. This E.M F. does not produce any potential difference between B and B′ and hence has no effect on the circuit or on the behaviour of the motor.

(3) The armature currents produce a reaction cross flux along the axis BB′. This flux will be in phase with the armature current, and in cutting this flux the rotating conductors will have an induced rotation voltage along the axis AA′ which axis can be modified by shifting the brush positions. Like

the transformer E M F , and for the same reason, this voltage has no effect on the motor circuit

(4) This reaction cross flux will have a transformer action on the armature coils, producing the usual back E.M.F. of self-induction 90 degrees in phase behind the current and along the axis B′B.

The Compensated Series Motor. Now the low-power factor of the motor is due to the inductive effect, i.e. the reactance of field and armature The field reactance can be minimised by using a relatively low field strength, a large number of poles and a low flux per pole. The field reactance, however, is a necessary evil since it is caused by the field flux upon which the driving torque of the motor depends. The armature reactance, however, is due to the armature cross flux, which is along an axis such that the armature currents experience no resultant torque in passing through it. This flux is therefore of no use in producing torque, and can be neutralised and eliminated. The neutralising can be effected by providing a coil at right angles to the main flux connected in reverse series to produce a magnetic effect equal and opposite to the cross flux, as shown diagrammatically in Fig 88. For complete neutralisation this winding should be distributed in the same manner as is the armature winding If the brushes are set in the geometrical neutral position, the compensating winding will require to be at right angles to the main field winding

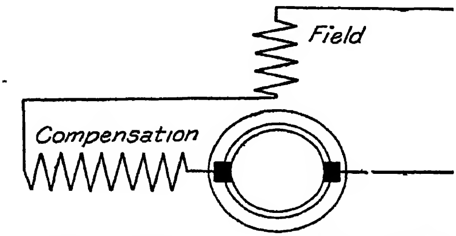


FIG 88 —Conductive or Forced Compensation.

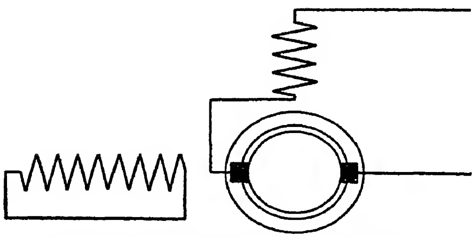


FIG 89.—Inductive Compensation

This compensating winding can be either in series with the main field and armature, as in Fig. 88, or it may be a winding closed on itself and producing its field by induction from the armature, as in Fig. 89 These two methods are known as

"Conductive" and "Inductive" compensation respectively. The conductive or "forced" compensation is theoretically the more perfect, any desired degree of compensation can be supplied and it is much used in practice. The inductive method, depending on transformer action, introduces a slight phase displacement but has the practical advantage that the number of turns do not need to be carefully chosen and a heavy section bar winding with light insulation can be used.

This compensating coil was the first step in the improvement of power factor. A further very obvious device for the same purpose is to reduce inductive effect by using a low frequency.

A low frequency, however, gives rise to generation difficulties, alternators are unduly inefficient and expensive for low frequencies; further, since the load factor of a railway supply is usually low it is desirable to combine with it some industrial load, and for this purpose again a low frequency is objectionable. The result is a compromise, 15 or $16\frac{2}{3}$ cycles being standard in Europe and 25 cycles in America and England.

The inductive effect can be further reduced by using a small air-gap, a low flux density and an unsaturated magnetic circuit, also a large number of poles and a low flux per pole.

A low flux per pole will necessitate a greater number of armature ampere turns per pole in order to obtain the requisite torque, and hence the ratio of armature to field ampere turns is much higher than for D.C. motors. The number of armature ampere turns is only limited by considerations of heating, if the compensation is satisfactory, but to accommodate the increased ampere turns the armature diameter has to be greater than for a D.C. machine of equal rating.

While the compensating coils described are able to neutralise the cross flux due to armature reaction, the effect of the transformer E M.F. remains.

As has been shown, with the brushes in the geometrical neutral position the coils undergoing commutation are in the position of maximum mutual inductance with respect to the main field winding.

If the armature coils have a low resistance and inductance. large circulating currents will be produced in the coils short-circuited by the brushes.

These currents cause excessive sparking, increased armature losses, a reaction which weakens the main flux and the torque but improves the power factor. Since it is undesirable to

improve power factor at the expense of efficiency, the circulating currents should be minimised by suitable design

The best way is evidently to neutralise the transformer E.M F., and for this purpose a commutating pole can be provided, placed like the compensating field between the main poles and having a coil connected in shunt across the supply. The E M F. induced by it will therefore lag approximately 90 degrees behind the main flux, as does also that of the transformer E M F.

Now it is evident that the effect of this commutating pole depends on the speed of rotation and can therefore only balance the transformer E.M F. at one definite speed. It may do so approximately over a limited range of speed, but is practically useless at starting, and to meet the difficulty at starting two other devices are employed, (1) to reduce the transformer E.M.F. by using a narrow brush so that only one coil at a time is short-circuited; by reducing the armature turns per coil to a minimum, i.e. by using only one turn per coil, and (2) by increasing the resistance of the path of the circulating currents. This latter is effected by using a high resistance brush and by placing resistances between the armature windings and the commutator bars, as shown in Fig. 90. These resistance connections are usually of Eureka wire and are located in the slots, below the armature windings This is still the practice of the Westinghouse Co. Resistances so placed carry current only when in the neutral commutating zone and hence produce no useful torque, and the Siemens-Schukert Co (Berlin) preferred to make them form a complete auxiliary winding distributed over the whole armature and so placed as to be in the middle of the main pole face when carrying current. A 10 per cent. increase of torque was obtained in this way without increasing the armature size.

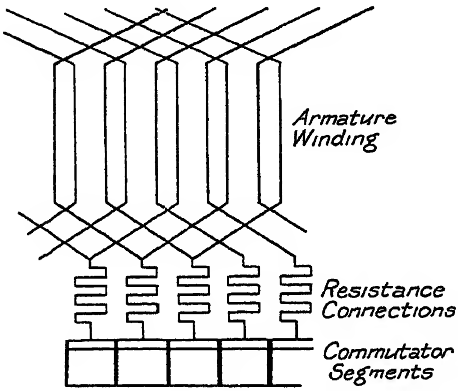


FIG. 90—Arrangement of Resistances.

The reduction of armature turns per coil to one limits the

permissible armature voltage by considerations of the largest possible diameter of commutator and narrowest width of segment and brush. Hence for moderate outputs, 200--300 volts is the usual pressure used, while larger motors have been made satisfactorily for pressures up to 450 volts and without resistance windings, which, however, are essential where a high starting torque is required.

Taking into account the load current as well as the transformer effect, 6 to 8 volts is stated to be the maximum permissible E.M.F. in the short-circuited coil if resistance leads are used, and about half of this if not This E.M.F. is usually slightly higher than the normal volts per commutator bar at the full line voltage, and this causes designers to lean towards large commutators, a large number of bars and low armature voltage.

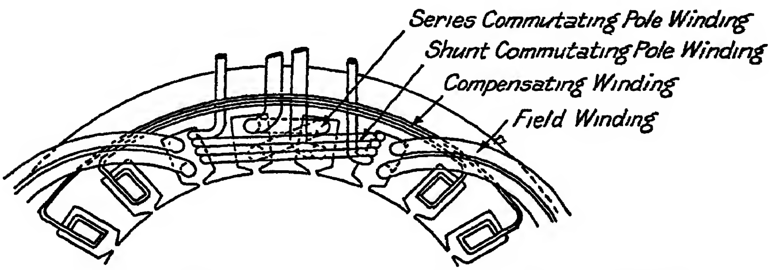


FIG 91 —Series and Shunt Commutating Poles (Siemens)

Since a commutating pole excited with series current is required for neutralising the E.M.F. set up by commutation of the main current, exactly as in a normal D.C machine, the commutating pole has often compound excitation—a series coil in series with the main current and proportional to it in strength, and a shunt coil connected across the supply voltage. The shunt coil then neutralises the transformer E.M F. while the series coil neutralises the reactance E M F. due to commutation of main load current.

Fig. 91 shows diagramatically the arrangement adopted by the Siemens Companies, and the arrangement of windings gives a minimum of mutual induction between the series and shunt coils The Oerlikon Co (Switzerland) uses a single series commutating coil shunted by a non-inductive resistance, as shown in Fig. 92, the flux so produced corresponding in magnitude and phase to the vector sum of series and shunt fluxes of a compound

commutating pole. This system is used on the Lötschberg-Simplon Tunnel locomotives.

It is interesting to note that some of the locomotives of the New York, New Haven & Hartford Railroad, which are fitted with Westinghouse compensated series motors, are arranged to operate on either single phase or direct current. When working on D.C. the compensating winding acts satisfactorily as a commutating pole, and although the system involves some complication in the switch gear, it has been in regular operation satisfactorily for some years. Inductive compensation would evidently be useless for D.C. operation.

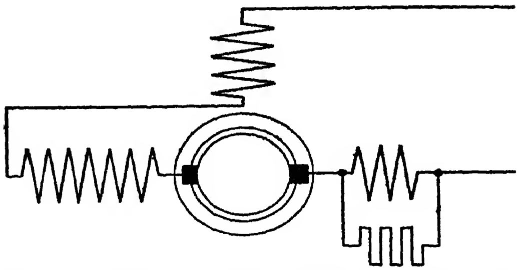


FIG. 92.—Series Commutating Pole, with non-inductive Shunt (Oerlikon).

The Repulsion Motor. In the repulsion motor the transformer effect, instead of being neutralised and eliminated, is made to produce the main driving torque.

Referring to Fig. 87, it was seen that the transformer effect produces a voltage between the points A and A′. If brushes are placed at these points and short-circuited a heavy current will flow through the armature, producing a torque on the conductors. There will be no resultant torque on the armature since the torque due to currents in conductors between B and A is exactly balanced by that due to currents in conductors between B′ and A. If the brushes, still short-circuited and with the armature stationary, are moved round into positions B and B′ there will again be no torque, since there is no pressure difference and hence no current Now let the brushes be moved into an intermediate position, as shown in Fig. 93. There will be an E M.F. between them, although this will be less than that existing between A and A′; consequently a current will flow through the armature and will produce a torque which will be actually

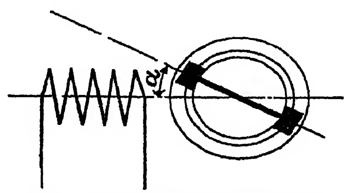


FIG. 93—Simple Repulsion Motor.

the difference between that produced by the conductors between A and B′ and between B and the top of the armature.

Another explanation of the principle which may appeal to some is that the short-circuiting of brushes A and A′, Fig. 87, produces a magnetic flux along the axis BB′ which being balanced produces no driving torque on the armature; it is therefore only necessary to give the brushes a lead in order to produce a driving torque which will cause rotation of the armature. Shifting the brushes backwards to an axis on the other side of AA′ will evidently reverse the torque and cause reversal of the direction of rotation.

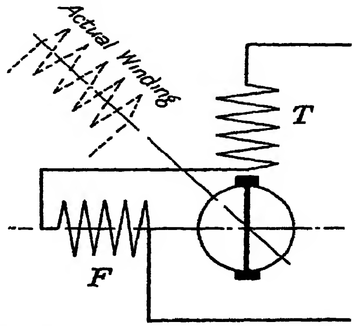


FIG 94—Equivalent Stator Coils of Repulsion Motor

The short-circuited brushes are the distinguishing feature of all repulsion motors.

The field winding is distributed over the stator as in the case of the series motor, and to assist in consideration of what happens in working it will be well to imagine the field as being the vector sum of two perpendicular fields and consequently able to be replaced by them, one field being parallel to the axis of the brushes and the other perpendicular to this axis, as shown in Fig. 94. This arrangement is to be considered as replacing the single stator field.

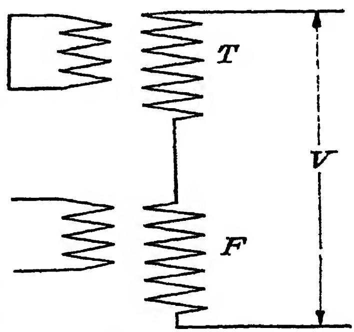


FIG 95.—Stator of Fig. 94 regarded as Short-circuited and Open-circuited Transformers in Series.

At starting, with the armature stationary, the relation of the two field windings F and T, will be exactly like that of the primary windings of two transformers which are connected in series, one transformer having an open-circuited secondary while the secondary of the other is short-circuited, as shown diagrammatically in Fig. 95.

Since F is an open-circuited transformer, it is evident that no energy can pass from it to the armature, but it provides the stationary torque-producing flux and its axis is therefore called

the Excitation Axis. All energy supplied to the armature must pass through T, which is therefore known as the Transformer or Energy Axis of the motor.

At starting, the flux from winding T passes into the armature, which is short-circuited at the points of maximum pressure difference. A current flows and sets up a reverse flux almost exactly equal and opposite to the main flux At the same time the winding F also induces a transformer voltage in the armature, but since the brushes connect points which have no pressure difference due to F, the winding F with the armature represents a transformer with open-circuited secondary. The arrangement behaves like two transformers, one having a short-circuited secondary, while that of the other is open circuited. Under these conditions it will be evident that the flux of winding T will be very small, being only that required to supply the armature copper loss, while the flux of winding F will be relatively large.

The greater part of the line voltage V will be across F, that across T being small, and since T is an almost non-inductive while F is a highly inductive circuit these two voltages, and hence the fluxes produced by their primary currents, will be almost 90 degrees out of phase with each other, F lagging behind T. The armature current will be 90 degrees in phase behind the flux T which produces it, and hence almost exactly in phase with the flux F, so that in consequence a strong starting torque is produced.

The stator is always wound in practice with the two windings which have been used to illustrate the working principles, both distributed over several slots but mutually perpendicular This is because a reversal of their position in the circuit will produce a reversal of the motor, which reversal with a single winding could only be obtained by shifting the brushes.

When the armature revolves, two additional voltages are introduced into the circuit, due to the conductors cutting the two fluxes, T and F, both these rotational voltages being exactly in phase with their respective fluxes

The cutting of flux T will induce a voltage across the horizontal axis, but the two halves balance and there is no path for a current to flow.

The cutting of flux F induces an E.M.F. in the circuit formed by the short-circuiting brush connection and so is practically an ordinary back E M F. of rotation, which must be overcome by an increase in the applied voltage in the short-circuited transformer, just as if a non-inductive resistance were placed

across the brushes instead of a short-circuit. The motor voltage therefore distributes itself differently between T and F; as the speed increases the voltage and flux of T increases and that of F decreases, and the current in the circuit decreases. This current is at starting, as was seen above, in phase with the flux F, but as the speed increases the current is drawn more towards T in phase and more out of phase with F. In consequence the power factor improves, but the torque falls off, due to two causes, viz., the reduction in current and the greater phase difference between current and the flux on which it acts. It is one of the characteristics, therefore, of the repulsion motor that a rise in power factor is always accompanied by a decrease in torque.

From the fact that the windings F and T are 90 degrees apart from each other in phase and are also 90 degrees apart in space, it follows in effect that the resultant stator field is a rotating one. (If the two fluxes are equal in value the resultant will be a uniformly revolving field, like a two-phase induction motor, while if they are not equal the field will be an elliptical one.) At synchronous speed the armature is stationary relative to the field and there will be no core losses and no currents in the coils undergoing commutation so that commutation will be influenced by the reactance voltage only. The repulsion motor therefore has good commutating characteristics, but above synchronous speed the armature flux and circulating currents in the commutated coils increase rapidly, a feature which limits the maximum speed to that in the neighbourhood of synchronism. On low frequency systems, therefore, the repulsion motor must be inherently a low-speed machine with few poles, so that this class of motor is not economical in size and weight for the low frequencies desirable for series motors which run at about twice synchronous speed The repulsion motor is therefore more suited to moderate frequencies, such as 25, compared with the 15 desirable for series motors. On the other hand, the operating voltage is not so limited and the stator of a repulsion motor can be wound for full line voltage, like an induction motor. Since, to produce a torque, part of the stator winding must be inductive, the power factor of the repulsion motor must be comparatively low, like the series motor

In order to make it possible for armature currents to neutralise the excitation stator flux and so improve the power factor, the compensated repulsion motor was introduced, but before describing this motor, a modification of the repulsion motor should be considered.

The Brush-Shifting Repulsion (Déri) Motor. In the discussion on the simple repulsion motor it was shown that the driving torque of the motor varies with the position of the brushes It would theoretically be possible to control the speed and direction of rotation of the motor by shifting the brushes, but such a method presents two practical difficulties: (*a*) a small movement of the brushes would produce a large variation in torque and the machine would therefore be very sensitive, and (*b*) when the brushes were in the position corresponding to zero torque there would be excessive circulating currents caused by transformer action in the armature coils short-circuited by the brushes.

These difficulties have been ingeniously overcome in the Déri repulsion motor by the use of a double set of brushes, as shown in Fig. 96, one set (AA) being fixed permanently in position along the axis of the stator winding, while the other set (BB) is arranged on a movable rocker so that they can be displaced relatively to the fixed brushes. Comparing this diagram for a moment with that for the simple repulsion motor, Fig. 93, it will be seen that in the latter case the magnetic axis of the armature is the same as the axis of brushes, while in the Déri motor the magnetic axis is the line bisecting the angle between the fixed and movable brushes, each pair of which are connected together as shown. This has the important result that in the Déri case the brushes must be moved through twice the angle which would be necessary to produce the same angular displacement of the magnetic axis for the simple repulsion motor, and the machine is therefore only half as sensitive to brush position. Furthermore, when the movable brushes are brought back in line with the fixed brushes (when the angle α is zero), i.e. when the motor is at rest, there is no current at all in the armature, which is entirely open-circuited. As the angle α is increased, more of the armature is short-circuited and acted on by the stator, and more torque is produced

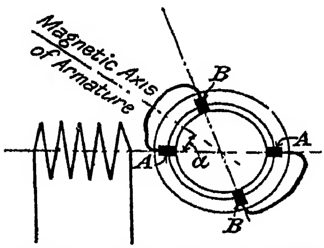


FIG. 96.—Déri Brush Shifting Motor

The Déri motor is therefore a variable-speed machine and can be controlled and reversed by the simple mechanical rotation of the brushes by a handwheel and gearing, there

being no need to switch off the stator current when at rest.

The commutation at speeds in the neighbourhood of synchronism is equal to that of other types of repulsion motor and is not affected by the position of the brushes At other speeds the commutating conditions at the fixed and shifting brushes are not identical, and whilst those at the fixed brushes can be improved by the use of commutating poles, the same device cannot be used for the others owing to their variable position.

This type of motor is manufactured by the Swiss firm of Brown, Boveri & Co. In practice a number of sets of brushes are provided, the number of each being the same as the number of poles.

The Compensated Repulsion (Winter-Eichberg) Motor. The arrangement of this type of motor is shown diagrammatically in Fig 97, from which it is seen that the armature has two brushes short-circuited along the transformer axis, and at right angles to this axis is another pair of brushes called exciter brushes connected in series with the stator current

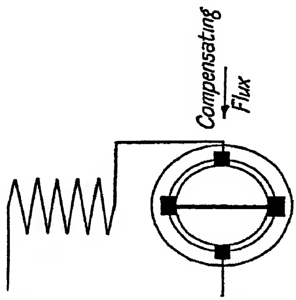


FIG. 97.—Compensated Repulsion Motor (Winter-Eichberg)

With the motor stationary there will be, as in the simple repulsion motor, a small flux along the horizontal axis, 90 degrees in phase behind the current, which causes by transformer action a short-circuit armature current along the horizontal axis in phase opposition to the stator current. There is in addition a strong vertical flux, in phase with the main armature current For the effect of the short-circuit current is to make the horizontal flux very small, and hence most of the applied voltage is absorbed in the inductive armature circuit and a strong flux is therefore produced along the vertical axis. This horizontal flux and the short-circuited current are evidently in the best phase and direction to produce a torque.

Now this horizontal flux completes its path through the stator iron and the net effect of the series connection through the " exciter " brushes is therefore to transfer the excitation winding from the stator to the armature.

As soon as the armature begins to rotate, two new rotational E.M.F.'s are introduced, due to cutting the horizontal and

vertical fluxes respectively That caused by cutting the horizontal flux is a true back E.M F between the exciter brushes, and hence the net voltage across the exciter brushes will decrease as the speed increases The E M F. caused by cutting the excitation flux tends, as was seen in the case of the simple repulsion motor, to neutralise the E M F. of self-induction. At the particular speed at which this E M F. exactly compensates the self-induction, the excitation flux will be completely neutralised and the machine will be operating at unity power factor, and above this speed the power factor will be a leading one

If the armature and stator turns are identical this speed, which is the running speed of the motor, will be the speed of synchronism For any other ratio of armature and field turns this speed will have another value, which, however, will be a definite value for any given ratio Since, however, it is always desirable that the transformer and excitation fluxes shall be equal, the correct armature current to correspond to any desired number of armature turns can be obtained by using a transformer connected as shown in Fig 98. The running speed is therefore always about the speed of synchronism.

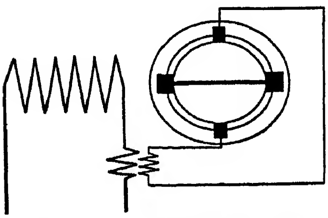


FIG 98.—Modification of Fig. 97.

If the transformer is arranged with tappings to produce a variable ratio, there is then the advantage that at starting the excitation flux can be reduced, thus reducing the circulating currents caused by its transformer action in the coils undergoing commutation, while at synchronous speed this effect disappears altogether and leaves only the usual reactance voltage to be dealt with.

The object stated in the last paragraph of the description of the simple repulsion motor is thus seen to have been achieved in the case of the compensated repulsion motor, the self-compensation is complete and the machine works at unity power factor when running at synchronous speed. It will be of interest to note that the motors supplied to the London, Brighton & South Coast line by the A E.G Co. (Berlin), and recently by the General Electric Co. (England) are of the Winter-Eichberg type.

The Series Repulsion (Alexanderson) Motor. A modification invented by Alexanderson of the General Electric Co.

(U S.A) is of interest and is shown diagrammatically in Fig 99. The Alexanderson motor can be started up as a repulsion motor, after which the short-circuit connection across the armature is opened and the machine operates as a compensated series motor. When thus connected the compensating (exciting) winding is also given an auxiliary excitation in shunt to produce a commutating pole effect. Experience has shown that the repulsion type of machine is inferior to the series type for general railway work, though its commutation is somewhat superior at low speeds; and Alexanderson's modification in combining desirable features from each, those of the repulsion motor for starting and those of the series motor for running, appear to have advantages over either type, and furthermore speeds considerably above synchronism are obtainable.

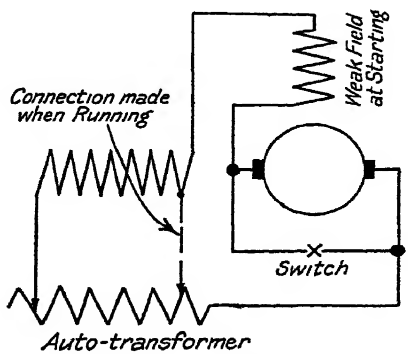


FIG. 99.—Alexanderson Motor.

A locomotive equipped with this type of motor has been operating satisfactorily for some years on the New York, New Haven & Hartford Railroad, but this interesting type of motor has not otherwise been employed for traction work, probably because the General Electric Co. (U S.A.) do not handle alternating current traction work to any large extent.

Control of Single-Phase Motors. Of the various types of motor which have been described the control of the Déri motor is the simplest, all that is required being an arrangement of gearing by which the driver can shift the position of the brushes of the motors. No doubt a suitable arrangement could be developed for starting a number of Déri motors on various cars of a multiple-unit train, but it has not been done and the Déri motor remains essentially a locomotive motor.

For all other types of single-phase motor the speed is controlled by means of voltage variation, which can be obtained in three ways, (*a*) by tappings on the low tension side of the transformer, (*b*) by an induction regulator, and (*c*) by a combination of (*a*) and (*b*) It will at once be seen that any of these arrangements render the use of rheostats unnecessary; each controller

notch is therefore a running notch, and series parallel control is not required.

Simple repulsion motors can be operated at the full voltage of the supply, but it is usual to use a transformer and wind the motors for a lower pressure; further this arrangement allows of some low tension current being available for the control circuit, compressors, heating and lighting

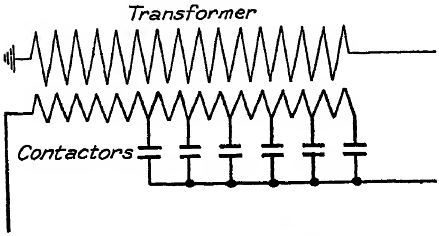


FIG 100.—Contactors arranged for Open-Circuit Transition.

The method of voltage variation by transformer tappings can be arranged for either open-circuit transition or closed-circuit transition The open-circuit transition is shown diagrammatically in Fig 100, which shows a number of tappings connected through contactor switches to the motors. This arrangement has the merit of simplicity and allows of the use of the minimum number of contactors, but it involves breaking the circuit in passing from notch to notch which produces jerky acceleration and arcing at the contact tips of the contactors.

In the closed-circuit transition, shown in Fig. 101, two con-

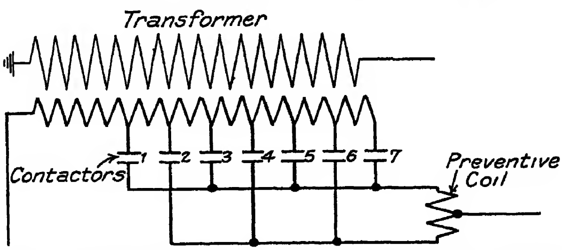


FIG. 101.—Contactors arranged for Closed-Circuit Transition.

tactors are in at once, which involves the use of a reactance coil, usually known as a "preventive" coil. It will be appreciated that the various tappings are all points of live electromotive force, and if two contactors are closed simultaneously even for a moment a complete short circuit of the transformer would result. (The student will call to mind a somewhat parallel instance in the case of a battery charging switch, Fig. 102, in which the moving contact is divided into two parts with a

resistance between them, so that in moving across successive contact studs there is no interruption of the circuit and only a limited short-circuit current is taken from each cell as its contacts are passed over) The preventive coil consists of a laminated iron core on which is wound a single coil, a tapping being brought out from the centre point. Such a coil will offer a high impedance to an alternating current passing through its winding from end to end, but will offer practically no choking effect to an alternating current between the centre point of the windings and the two ends, since in the latter case the currents are in opposite directions, their magnetic effects are equal and opposite and therefore neutralise each other.

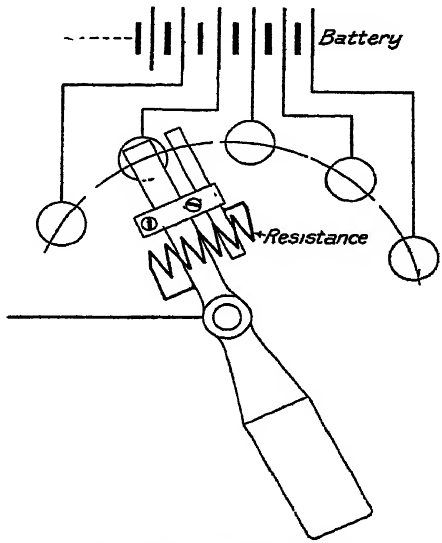


Fig 102.—Battery Switch.

Referring to Fig. 101, it is seen that the odd and even numbered contactors are arranged in two groups with the preventive coil connected across them, the connection to the motor being taken from the middle point of the preventive coil. Suppose now contactors 3 and 4 are both closed The preventive coil acts as an auto-transformer with a ratio of 2 to 1, and the potential at the middle point will be midway between the potential of contactors 3 and 4. To increase the voltage, contactor 3 is opened and 5 is then closed, the current during transition passing from 4 contactor and one-half of the preventive coil The voltage supplied to the motor during the three stages of transition is therefore as follows :—

3 and 4 contactors closed	—voltage midway between 3 and 4.
3 opened, 4 remaining closed	—voltage of 4, slightly reduced by the reactance of half the preventive coil.
4 and 5 contactors closed	—voltage midway between 4 and 5.

Thus the transition takes place smoothly, without open or short circuit.

Since, except for the momentary transition stage, each contactor carries one-half the current, the contactors may be designed to carry only half the motor current, but at least one more contactor is required for closed-circuit than for open-circuit transition

The above method can be extended by using a greater number of contactors and dividing the current between four at once, by the use of three preventive coils This gives a large number of available voltages and very smooth acceleration and is used for controlling large locomotive motors.

Induction Regulators. The second method of voltage variation to be considered is that of the Induction Regulator which consists essentially of an induction motor with a wound rotor, locked in position and capable of being rotated through about 180 degrees. The primary (stator) winding is connected to the supply voltage, while the secondary (rotor) winding is connected in series with the motor circuit. The voltage induced in the secondary winding depends on its position relative to the primary, and can be varied from a negative maximum value to a positive maximum. Thus the regulator is a negative or positive series booster, and if the normal motor voltage is 300 and a voltage of 100 volts is required at starting, then the induction regulator secondary must be wound for 100 volts and the transformer voltage must be 200. In the position of maximum negative boost, i e. at starting, the motor voltage will be 200 minus 100, i.e. 100 volts, which can be increased to 300 in the position of maximum positive boost.

The induction regulator therefore has the advantage of requiring no contactors, no preventive coils, and no starting tappings on the transformer ; and it produces an infinitely fine gradation of voltage and hence perfectly smooth acceleration.

Against all these advantages must be placed the fact that an induction regulator for a large motor is a somewhat large, costly and heavy piece of apparatus ; moreover being itself essentially a motor the mechanical torque developed is considerable and the apparatus must be strongly built to withstand the vibration caused by so heavy a pulsating torque. It must also be operated by a motor of several horse-power, so that the simplicity achieved is dearly bought. On account of the air-gap necessary between the primary and secondary of the regulator, the power-factor of the system is inevitably somewhat reduced.

Mr. F. Lydall has devised a method of using contactors with the secondary of an induction regulator in place of a preventive coil, the regulator primary being placed across the transformer. This allows of the same voltage gradation as does the simple regulator system, while the regulator itself may be of quite small size. This system is in use on the Prussian State Railways.

Contactors. All the methods described are in use, the induction regulator system being more suitable for locomotive work, but as a result of experience it is fair to say that practice is standardising on the contactor system with transformer tappings Contactors may be of the pneumatic or electro-magnetic type; if of the former, the design need differ in no respect from that of a direct-current contactor; while if of the latter type the pulsating nature of alternating current imposes several modifications. The magnetic circuit of the contactor must be laminated and arranged for the minimum air-gap in order to reduce the magnetising current Since the operating voltage of single-phase motors is low, the currents dealt with by the main contact of the contactors will be heavy, and precautions must be taken to avoid eddy currents in the contacts so that the magnetic blow-out action is not thereby impaired. The "shading pole" device is used to maintain a pull and prevent chattering of the contactor while the main alternating flux is passing the zero value. This is shown diagrammatically in Fig 103, the "shading" coil (which must only enclose a part of the pole face) consisting of a solid band of copper or preferably several turns of wire connected to a resistance. The circulating currents induced in this small short-circuited secondary are in lagging phase relationship to the current in the main coil and hence exert a pull on the plunger while the main flux is at zero.

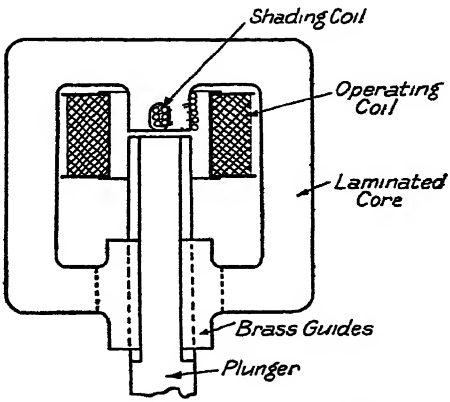


Fig 103.—Magnetic Circuit of Alternating Current Contactor.

A feature of the A C. contactor is that the operating current

immediately falls in value when the plunger is drawn up owing to the reduced induction, and allowance must be made for this characteristic in design

In cases where a motor-generator is provided, the control can be operated by direct current using D C. contactors, the particular advantage of this system being that batteries can be carried as a stand-by and for emergency lighting. The usual operating voltages of single-phase motors and auxiliaries are approximately as follows .—

Series motors of medium size	250 to 320 volts.
Series motors, large	400 to 500 ,,
Repulsion motors	750 to 1000 ,,
Compressors, air blowers, lighting and heating, and control	110 to 300 ,,

CHAPTER IX

THREE-PHASE AND SPLIT-PHASE RAILWAYS

Three-Phase Railways

From the point of view of ruggedness, simplicity and reliability the three-phase induction motor, owing to the absence of a commutator, has no equal, and it is not surprising that the attempt was made at an early stage in the history of railway electrification to utilise this type of motor for traction purposes, particularly since by its use power could be economically generated at the pressure and frequency required and transmitted to the motors without the necessary intermediary of transformers or sub-stations.

Regeneration. Furthermore, the polyphase induction motor has the valuable property of automatic regeneration without any additional windings or control appliances. A train driven by polyphase induction motors without any special apparatus will return energy to the line whenever it encounters a down grade steep and long enough to provide the energy, and will do so automatically and even without the driver being necessarily aware of what is happening.

As long as the locomotive is hauling, energy is taken from the line and the motors run at slightly less than synchronous speed, but when the train reaches such a down gradient that it tends by gravity alone to increase its speed, the motors, then running somewhat above synchronous speed, begin to regenerate, and energy thus returned to the line will hold the train at this constant speed of slightly above synchronism. This is a very valuable property, particularly in mountainous country where the gradients are long and steep; not only, or even principally, on account of the saving of energy, but particularly on account of the simpler and more reliable control of the speed of the train which does not depend on the skill of the driver. When such descents have to be made by steam trains, or electric trains not equipped for regeneration, the wear on brake shoes and tyres is very considerable; the brake blocks may become very hot and

the large amount of heat produced in the tyres has even been known to cause a wheel to loosen from its axle ; further, since the brake cylinders, owing to air leakage, cannot be relied upon to provide a constant retarding force on a long gradient, it is the practice to allow the train to descend in a series of short runs, i.e. to reach a certain safe speed, apply the brakes with full force and bring the train nearly to a stand, after which the brakes are fully released and the cycle repeated. During release, the brake reservoirs are restored to full pressure and full brake force is again at the disposal of the driver, on whose skill, however, the safety of the train depends. The long tale of accidents due to drivers allowing the train to reach speeds beyond the control of the brake is sufficient explanation of the attractiveness of electrical regeneration to railway engineers who have to operate over mountainous districts, and the extensive use of the three-phase system in Northern Italy is probably to be ascribed in large measure to the mountainous nature of the country and the field thereby provided for regeneration. It should also be mentioned that at the time when the three-phase system was installed in Italy, no single-phase nor high voltage D C motor had been developed.

The saving of energy, though valuable, is a secondary consideration ; the return of energy to the line at a time when there may happen to be no train or other load to utilise it constitutes an embarrassment, and an artificial load, generally a water-rheostat, has usually to be provided at the generating stations to meet this emergency.

Overhead Trolley Lines. The first difficulty met with in any three-phase distribution system is the need for at least two trolley wires (the track rails forming the third conductor), and since these must be suspended so as not only to be clear of structures and of each other everywhere, but also so that each may always clear the current collectors of the other phase, the difficulties of the overhead system are much greater than when a single trolley wire is used, and the limits of practical deviation are correspondingly reduced. The spans must accordingly be short and the trolley wire frequently anchored against lateral displacement. The special work at turnouts and crossings is complicated by the crossing of wires at different phases, which requires many insulated sections, and generally it will be realised that these difficulties, inherent to a three-phase overhead lay-out, constitute a very real objection to the system except for isolated places in which the lines do not encounter many large towns.

Polyphase Motors. The next restriction to be considered is imposed by the motor. Although research work is still proceeding with polyphase variable speed commutator motors, no satisfactory design has yet been developed, and the induction motor holds the field as the only type available for three-phase working. This motor has a " shunt " or constant speed characteristic, and although a measure of speed control can be obtained by inserting resistances in the rotor circuit, the method is limited in range and wasteful of energy The range of running speeds can be economically extended by " cascade " running (described later) and by changing the number of poles, but the motor remains essentially a constant speed machine. As such, many of the objections urged against the shunt motor for traction work (Chapter VI) will also apply to it, notably that a small variation in wheel diameter causes an unduly large part of the load to be taken by the motors driving the larger wheel. For this reason and on account of low acceleration the motor is quite unsuitable for multiple-unit trains, and its use is practically confined to locomotives. Even then the locomotives are practically obliged to run singly, for two locomotives on the same train would not share the load equally if the wheel diameters were not equal. This can be compensated for by inserting resistance in the rotor of the faster motor, but the device is unsatisfactory The induction motor therefore is restricted to locomotive working where long main line runs at steady speed can be made, with infrequent stops and low acceleration. The constant speed on up grades makes the peak loads on the line necessarily heavier than with the D C or single-phase systems

The only three-phase railways of consequence are the Italian State Railways, smaller installations existing in Switzerland, South Spain and U S A , as is shown in the table on next page.

Cascade Connection. The method of reducing speed by inserting resistance in the rotor circuit to cause " slip " can be improved upon by using two motors, the stator of the second being supplied with current from the rotor of the first. This arrangement is known as " Cascade " or " Concatenation " (*Latin*—chained together) and is shown diagrammatically in Fig 104. The two rotors must be mechanically coupled or geared together, and the rotor of the first or main motor must be wound with the same number of poles as the stator ; the secondary motor must be wound with the same number of poles as the first, but the number of poles on its rotor is unimportant The stator of the main motor is then connected to the supply,

LIST OF CHIEF THREE-PHASE SYSTEMS

Railway.	Route Miles	No of Locomotives	Cycles	Trolley Voltage	Voltage on Motors	Date installed.	Builders of Locomotives
1 Italian State Railways	272	55	$16\frac{2}{3}$	3,400 to 3,700	3,000	1901	Italian Westinghouse Co, Ganz Co (Austria); Oerlikon (Switzerland)
2. Burgdorf-Thun Railway	35	5*	40	750	750	1899	Brown, Boveri
3 Simplon Tunnel Railway	47	4	$16\frac{2}{3}$	3,000	3,000	1905	Brown, Boveri
4. Great Northern Railway (U S A.)	7	4	25	6,600	500	1909	G E (U S.A)
5. Southern Railway (Spain)	14	5	15	5,500	5,500	1907	Brown, Boveri

* Also 6 motor cars

while the slip-rings of the secondary motor are connected to a three-phase rheostat. The synchronous speed of the set is then half the synchronous speed of the main motor. It will be seen that the cascade system necessitates two motors, which, if the

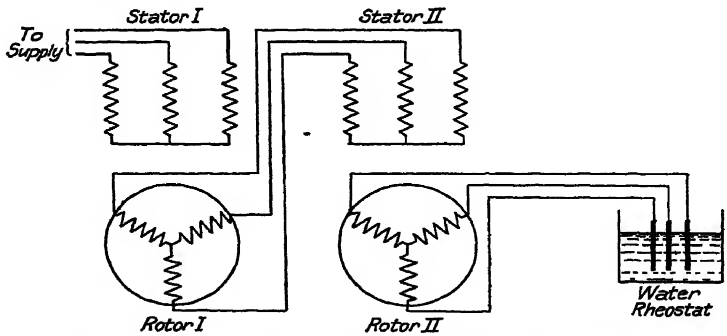


FIG. 104—Cascade Connection of Three-Phase Motors.

cascade connections are later to be opened and the motors run in parallel, must have the same number of poles, while the stator windings of the secondary motor must be designed to operate with full supply voltage, and also with the rotor voltage

of the main motor. To this objection must be added the low power factor of the set which rarely exceeds 80 per cent. in the best designs

Pole Changing. Fig. 105 shows an arrangement for changing the number of poles of one phase of a stator winding, which will serve to illustrate the principle of pole changing.

The diagram shows one phase only for three-phase winding, the other two-thirds of the stator slots being shown ready to receive the windings of the other two phases

Some of the Italian State Railway locomotives are arranged for four running speeds by a combination of the cascade and pole-changing systems.

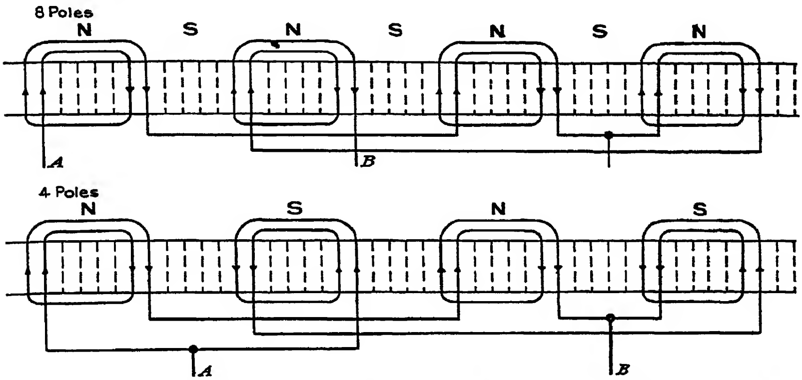


Fig. 105.—Connections of One-phase at a Three-phase Stator Winding to produce 8 and 4 Poles.

The stators of the main and secondary motors are each wound for the same number of poles and it is evident that if the poles are changed in the ratio of 2 to 1, the speeds obtainable will be in the ratio of 1 : 2 . 4 Since this variation is usually too great the poles are arranged for a change from 8 to 6 poles, so that the speeds obtainable are in the ratio of 1 : 1·33 : 2 : 2 66.

In the case of the latest Italian locomotives the actual speeds are 37·5 : 50 : 75 · 100 kilometres per hour. The four speeds can also be obtained without cascade connection by using two entirely separate stator windings to each motor, of different numbers of poles, each of which can vary the number of its poles, but this allows of only one motor working at a time and causes the combination of cascade and pole changing to be generally preferred.

Air-Gap. As with all induction motors the large proportion (70–90 per cent) of the stator ampere turns are required to overcome the magnetic reluctance of the air-gap, and it is therefore desirable for high efficiency and power-factor to keep the air-gap as small as possible. Although in railway motors the air-gap is usually made considerably higher than in stationary motors, the bearings must correspondingly be liberally designed and very carefully maintained against wear. The air-gap is usually about 2 mm in the case of the Italian and Swiss locomotives, while in the Great Northern Railway motors it is $\frac{1}{8}$ inch, as compared with about $\frac{1}{4}$ inch obtaining in direct current machines of moderate size. The small air-gap is thus a very real objection to induction motors for traction work.

Voltage and Frequency. Although induction motors can be built for any frequency, a high frequency necessitates a small air-gap if power-factor is to be kept high. The voltage used on the Simplon and Italian lines is 3,000 to 3,700 at a frequency of $16\frac{2}{3}$ cycles, but the Great Northern Railway uses 6,600 volts, 25 cycles, reduced by transformer on the locomotive to 500 volts. A very complete description of these systems is given in Burch, *Electric Traction for Railway Trains* (McGraw-Hill Book Co.).

Control and Rheostat. The type of rheostat used is preferably the liquid type The usual grid type is slightly inductive, which is a decided disadvantage, especially in cascade working where the inductance of the second motor is already added to the inductance of the circuit of the main motor It is stated that grid rheostats produce a phase displacement of 5 degrees lagging, while the liquid rheostat is non-inductive and may even possess a slight electric capacity. Furthermore the liquid rheostat allows of being operated to produce a perfectly even torque during acceleration, entirely avoiding the controller jerks familiar on all other starting devices. The liquid, a solution of carbonate of soda in water, is forced by air pressure into chambers containing iron electrodes, the height of the liquid (and hence the current passing) being governed by an automatic regulator. Provision is made for circulating and cooling the liquid

The operations to be performed in accelerating from standstill to full speed with simple cascade control are the following :—

(1) Connect motors for cascade running with rheostat in rotor circuit and apply full line voltage to the main stator.

(2) Cut out resistance until rheostat is short-circuited The speed will now be about half full speed

(3) Switch current off from main stator.

(4) By means of a change-over switch re-arrange either the main or both motors for single operation, with full resistance in the rotor circuit, and re-apply line voltage to the stator (or stators).

(5) Cut out all resistance until rotor is short-circuited.

Several variations of the cascade arrangement can be made, e g. (*a*) motors may start up in cascade, and the main motor only may be then connected into parallel, the secondary motor being disconnected ; (*b*) after cascade starting both motors may be connected into parallel. Both (*a*) and (*b*) give a 2-speed combination ; (*c*) for three speeds the primary and secondary motors are wound for a different number of poles, and after cascade starting are operated singly , (*d*) both motors have the same number of poles and either one or both of them are arranged for pole changing.

It will be seen that any of these starting systems is necessarily jerky, and this appears to be unavoidable.

Regeneration can be obtained with any of the speeds. either when running in cascade or with the poles changed.

It will be evident that the main motor of the cascade arrangement has to carry the magnetising current for the second and hence has greater losses and a higher temperature rise.

In the latest Ganz locomotives the two armatures are mounted on one shaft and the two stators are built inside one casing, making one unit of the two motors.

The Split-Phase System

The term " split-phase " is given by the inventor, Mr. Alexanderson, to a system which employs single-phase current on the trolley line ; converts it by a phase-converter on the locomotive into three-phase current and uses it to drive three-phase induction motors. The system has the advantage of using only one trolley wire but avoids the disadvantages of the single-phase motor, especially that of requiring a very low frequency, and since the phase converter is reversible full advantage can be taken of the regenerative qualities of the motors As originally proposed, two-phase driving motors were to be used, one phase being supplied directly from the line, and the other from the windings of a phase converter

The general principle of the phase converter is that if a two- or three-phase induction motor is run up to speed, current switched off and one phase only of the stator supplied with

single-phase current, the machine will continue to run as a single-phase induction motor, and in so doing a true rotating field will be produced in the rotor. As a result, E M F.'s will be induced in the other stator windings in exactly the same phase relations as if these windings had been connected to the polyphase supply.

This is shown diagrammatically in Fig 106, in which a two-phase converter is used to supply three-phase current for a three-phase motor. One phase is shown connected to the supply, while the other is connected to the centre point of the transformer. Three-phase current may be obtained from terminals A, B and F, and the student will recognise this arrangement as the well-known "Scott" connection for obtaining three-phase current from a two-phase supply. It will be remembered that the exact position of the tapping T varies with the amount of load taken, and in practice therefore T is made a variable tapping. The converter is used to supply current to two motors.

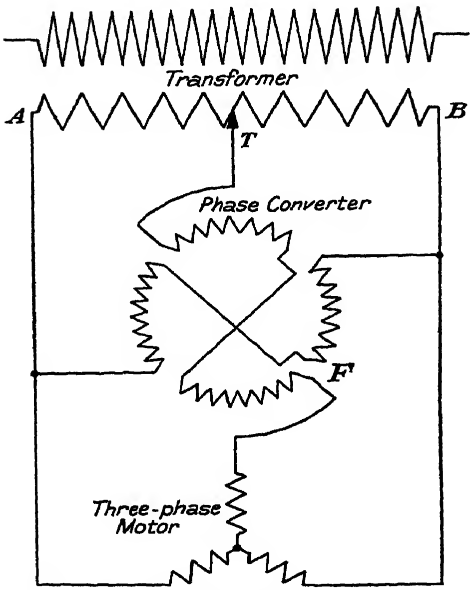


FIG. 106.—Diagram of Phase-Converter Circuits.

The split-phase system is in use on the Norfolk & Western Railway (U.S.A.) which has about 30 miles of electrified track including 3·8 miles of 2 per cent. grade. Eighteen double locomotives are in operation, each weighing 240 tons and capable of hauling very heavy mineral trains up to 3,000 tons up the severe grades at a speed of about 14 miles per hour. The motors are wound for both 8 or 4 poles, and the train descends the grade with the 4 pole arrangement at 28 miles per hour regenerating and hence braking electrically. The speeds mentioned are the synchronous speeds corresponding to 8 and 4 poles respectively.

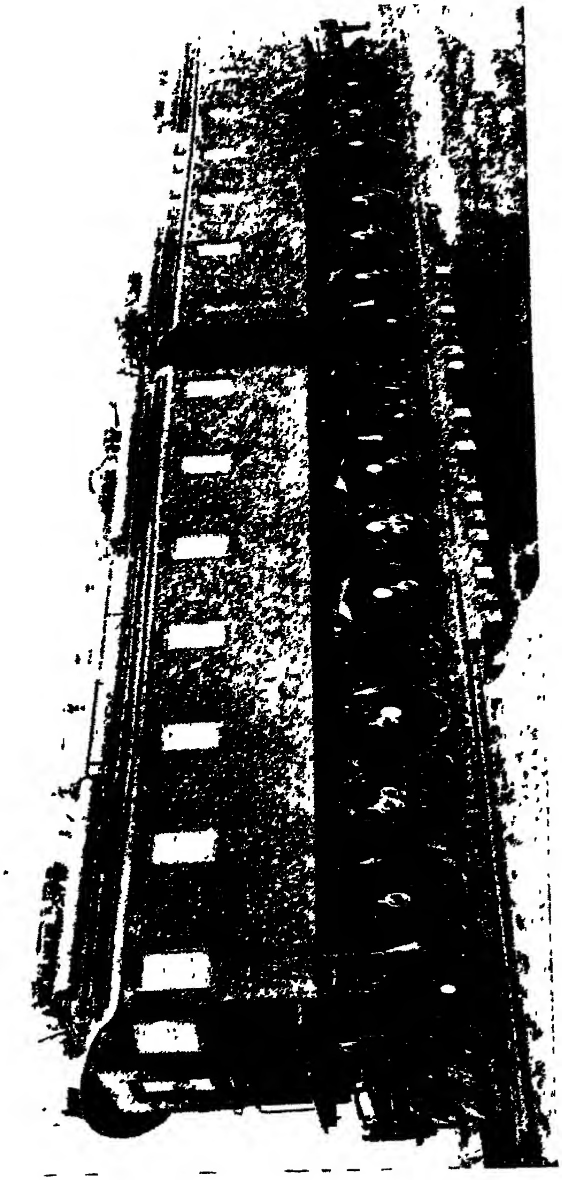


Fig. 107.—Norfolk & Western (Bluefield Division) Goods Locomotive.

Owing to the need for the phase converter, which could not be accommodated on motor coaches, the system is only suitable for locomotive working, and the limited ranges of speed render it unsuitable for general service and restrict its use (as in the case of the straight three-phase system) to specially steep gradients and heavy loads

The only other example of the split-phase system is found on the Pennsylvania Railroad (Altoona–Johnstown section) whose one locomotive, like those of the Norfolk & Western line, is notable in employing two motors to drive one and the same gear wheel, through flexible connections, as is seen in Fig 107.

The locomotives of both companies have been built by the Westinghouse Co , and it is interesting to note that the loads hauled by the Norfolk & Western are among the heaviest operated by electric power in any part of the world.

The Virginian Railway has 12 3-cab locomotives under construction by the Westinghouse Co , showing that the split-phase system is a pronounced success for the particular duty of hauling very heavy mineral loads on very steep grades.

CHAPTER X

BRAKES

In the opening chapters the importance of rapid acceleration, in order to allow of a high schedule speed, was stressed, but it must be remembered that a high rate of braking is equally important to produce the same result On tramcars the brakes are applied either by hand power or electro-magnetically, a power air brake being used in very hilly districts ; but on railways a power brake is a necessity, as the driver could not exert sufficient force for the purpose.

The brakes used on railway trains are of two types only · the Vacuum and the Compressed Air. The first is manufactured by the Vacuum Brake Co , and the best known make of compressed air brake is that manufactured by the Westinghouse Brake Co. In both types brake blocks are applied to the tyres of the wheels with sufficient force to absorb in heat practically the whole kinetic energy of the train ; and in both types that force is supplied by a piston working in a cylinder. In the vacuum brake, a vacuum is maintained on one side of the piston, and the force available is therefore limited to the 15 lbs. per sq in. atmospheric pressure. In compressed air brakes there is no such inherent limit to the piston pressure, and in practice some 50 lbs. per sq. in. is used. As a natural result the compressed air cylinder is much smaller and lighter than a vacuum cylinder for the same total pressure, and on some motor coaches it would be impossible to find room for the large cylinders required for the vacuum brake.

Owing to the great simplicity of the vacuum brake it has been adopted almost exclusively on English steam railways, whereas some of the Scottish lines use the Westinghouse brake ; for which reason rolling stock designed for through travel between England and Scotland has to be provided with both systems, acting on the same brake blocks and pull rods, and such coaches are marked "Dual Fitted" The Westinghouse brake is practically universal throughout America for steam and electric stock, and is

adopted throughout Australia In Great Britain lines which have electrified have, with very few exceptions, adopted the Westinghouse brake, and it must therefore be regarded as the standard for electric traction. On the other hand, all the electrified sections of the Lancashire & Yorkshire Railway and the Midland (Heysham line) use the vacuum brake; and on the Aldgate–Harrow section of the Metropolitan Railway electric locomotives are used to haul ordinary steam rolling stock fitted with the vacuum brake, and these locomotives have accordingly been "dual fitted." Also the Central Argentine, South African, Indian G.I P., and several Continental lines retained the vacuum system on electrifying. These are then exceptions to the general use of the Westinghouse on electric vehicles.

It may be mentioned that the Westinghouse brake allows of a train carrying a supply of high-pressure air sufficient for a short journey of a few stations Trains so arranged have no compressors but are charged up at each end of the journey

The Westinghouse Automatic Brake

The essential parts of this brake are as follows —

1 The electric circuit, switches, fuses, etc , supplying current through
2. The compressor governor, an air-operated switch, to
3. The motor compressor, a series motor coupled to an air compressor, delivering air at 90 lbs per sq in to
4. The main reservoir, which is connected by piping through
5. The isolating cock to
6. The driver's brake valve. From this valve compressed air passes through
7. The feed valve, which is adjusted to maintain a pressure of about 70 lbs. per sq. in in
8 The brake pipe, from whence it passes through the feed grooves of
9. The triple valve into
10. The auxiliary reservoir and from this reservoir into
11 The brake cylinder forcing out the piston which is connected by rods and levers to the brake blocks, thereby applying the brakes.
12. The hose couplings of strong canvas and rubber are the flexible connections between the coaches of the train, and
13 The coupling cocks control the air supply through the hose couplings

On steam trains the motor compressor and connections are naturally replaced by a steam operated compressor.

The two compressed air pipes, the "main" at 90 lbs per sq in, and the "train" or brake pipe, are continuous throughout the train, and a brake cylinder and operating valves—items 8 to 13—are supplied on each vehicle. Items 1 to 7 are generally supplied on motor coaches only, and all compressors on the train are usually operated together

The compressed air at 90 lbs per sq in is stored in the main reservoir carried under the motor car, and a "main" pipe runs the whole length of the train to connect all the main reservoirs together in parallel An auxiliary reservoir is fitted on each coach, trailer or motor, and the "train" or brake pipe at 70 lbs per sq. in is also carried throughout the train to connect all auxiliary reservoirs together in parallel

The compressor motor is series wound and is thrown straight on the mains without starting rheostats As soon as the desired pressure is reached in the main reservoir and "main" pipe, pressure on a flexible diaphragm in the compressor governor causes the governor switch to cut out, and the motor stops When this main pressure falls to 75 lbs per sq in the governor cuts in again, and the "main" pressure is thus automatically maintained. The various compressors are connected in parallel and arranged all to cut in and out simultaneously A safety valve is fitted on each main reservoir to prevent excessive pressure in case the governor should fail to cut out.

From the "main" pipe line a connection is taken to the driver's brake valve in all the driving cabs of the train, and a stopcock is fitted under each brake valve. These stop-cocks are kept closed except that in the cab from which the motor-man is driving. When the cock is open the compressed air passes up to the driver's brake valve, and if the valve handle is in "release" position the air passes through the brake valve to the "train" pipe.

In order to reach the auxiliary reservoir the air has to pass through a **triple valve**, so called because it accomplishes three separate duties according to the position of the valve, viz. :—

(i) The valve allows air to pass from the "train" pipe into the auxiliary reservoir until valve, reservoir and pipe all contain the same pressure. This takes place while the driver's brake valve is at the "release" position. See position A on Fig. 108.

(ii) When a service application of brakes is made, the valve cuts off the connection between "train" pipe and auxiliary

reservoir and admits a certain amount of air from this reservoir into the brake cylinder. This pushes the piston forward and applies the brakes See position B on Fig 108.

(iii) On releasing the brake the valve repeats operation (i) and also provides an exhaust direct to atmosphere for the air in the brake cylinder

The triple valve is a most important feature since the whole principle of the brake consists in balancing by means of the triple

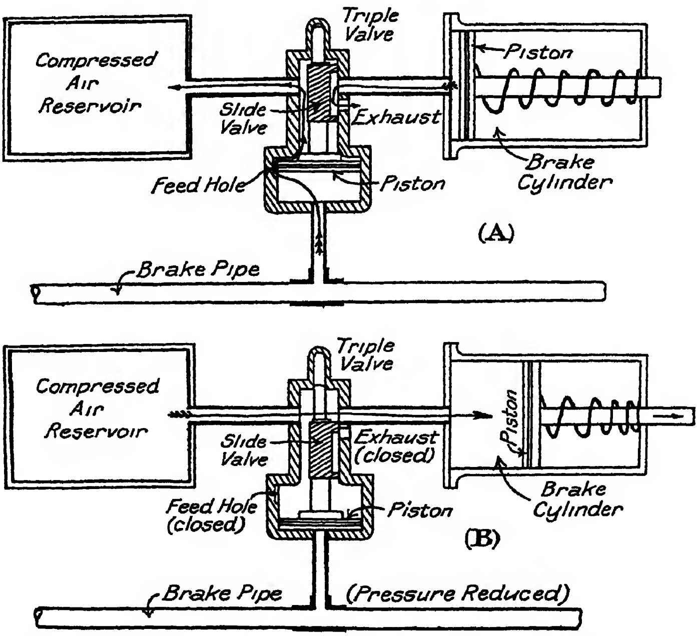


FIG 108.—Principle of the Westinghouse Automatic Brake.

valves the train pipe pressure against auxiliary pressure on either side of a piston. Fig 108 shows diagrammatically the principle of this valve. A reduction of pressure on one side causes this piston to move and operate the valve, and so allow a flow of air to the brake cylinder.

The Driver's Brake Valve is the apparatus operated by the driver. It has three connections, to (*a*) the "main" pipe, (*b*) the "train" pipe, (*c*) the atmosphere. The operating handle can be moved by the driver into five positions, thus :—

(1) **Release Position.** Main Pipe is connected direct to train pipe (short-circuiting the feed valve), and thence via the triple valve to the auxiliary reservoir When this is charged up to almost full train pipe pressure, the handle can be moved to the

(2) **Running Position,** which shuts off the direct supply of air from the main reservoir to the train line and permits it to pass only through the feed valve, which is set to shut off at train pipe pressure

(3) **Service Application Position.** Air is now allowed to escape to atmosphere from the train pipe, upsetting the balance of pressures on the various triple valves. The triple valve moves, shuts off the connection between train pipe and auxiliary reservoir, and allows air from the auxiliary reservoir to flow into the brake cylinder The piston moves forward, and by means of pull rods and levers its force is transmitted to the brake blocks, and the brake is applied. If the handle be now moved back to the

(4) **Lap or Neutral Position** the brakes will continue to be applied at the same pressure If the handle is now moved to "service application" again, operation (4) will be repeated, and a further supply of air be admitted to the brake cylinder, i e the brakes will be applied more strongly than before according to the distance the handle is moved towards the full service notch and the time it is left there By repeating these service applications, the driver can introduce any desired pressure into the brake cylinder.

On moving back to "release" position air from the main pipe passes into the train line, increasing the pressure in the train line and thus causing the triple valve on each car to move, recharging the auxiliary reservoir and opening the brake cylinder to atmosphere. Springs now move the piston back again, and pull the brake blocks off the wheels.

(5) **Emergency Application.** If the handle is moved over to the extreme position, the train pipe pressure is very rapidly exhausted, and brakes are applied very quickly and with maximum force.

Note. If the handle is left too long in the release position, the train line will be charged up to above normal pressure, and ultimately to full main line pressure. If now set to "running" position, the train line will adjust itself through the feed valve to its normal pressure. If the train line is charged up to full main

line pressure by leaving the handle too long in "release" position, an application of the brakes might be far too powerful and cause the wheels to skid Moreover if the handle is then brought to release, there may be insufficient pressure difference to operate the triple valve, and it will not be possible to release the brakes.

A general arrangement of the brake is shown in Fig 109. The position shown on the right of this view is repeated on each trailer car

Safety Features. If a coupling should part and the train break in two the breakage of the hose couplings on the train pipe would immediately exhaust this pipe and so produce the full emergency application of brakes on both portions of the train. A leakage of air at any part of the train pipe has the effect of applying the brakes. Emergency cocks are provided in guards' vans, and in the vestibule of each car. If any such cock be opened the train pipe is exhausted and emergency application of brakes is produced.

If the brake on any vehicle should fail, the reservoirs, etc., on such vehicle can be isolated by means of cocks provided for the purpose without interfering with the operation of the brakes on the rest of the train.

It should be pointed out that the brakes cannot be released gradually. If too strong an application has been made, the only means of correcting it is to release the brakes completely and to re-apply them to the desired force. To overcome this objection, an electric attachment has been devised, known as the Electro-pneumatic Brake, which is described later.

General Remarks. The pressures of 90 and 70 lbs. per sq in. for the main and train lines respectively are those recommended by the makers, but railway companies often vary them slightly to suit their individual conditions Thus the L & N.W. railway operates at 95 and 65, and the Victorian Railways at 100 and 77 lbs. per sq. in.

Students are often surprised to learn that the compressor motor can be switched direct on to the line without a starting rheostat. The series motor has of course a high inductance, and a geared compressor starts nearly light for the first few revolutions. The L & N W.R compressor motor B.T.H. type CP 30 takes 40 amps. momentarily on 600 volts, falling to 12·5 amps steady current. The motor is rated at 8¼ B.H P. and the compressor at 36 cub. ft of free air per minute. The motor drives the compressor through 1 to 5 64 gearing. No difficulty is

experienced in this direct starting of compressors on 1,500 volts

Gauges. The driver's duplex gauge is fitted with two indicating pointers, one, coloured red, connected to the main pipe; and the other, black, connected to the train line. The driver can then see at a glance what the condition of the brake is.

Control Governor. Most train control systems pass the main control current through a control governor, an air-operated switch similar in design to the compressor governor, but functioning in an exactly contrary manner. The air side of the control governor is connected to the train pipe and the apparatus is adjusted to break the control circuit if the train line pressure falls below 50 lbs. per sq. in This prevents a motor-man from starting his train until his brakes are pumped up to an operating pressure, and stops the train if such pressure should fail from any cause.

The Dead Man's Handle has been described previously in Chapter IV. On releasing the handle the emergency valve lifts and exhausts the train line to atmosphere, applying the brake with full emergency application.

Trip Cocks. In systems where electric signalling is used, the signal may be reinforced by a trip system which automatically stops the train if the driver should pass it at danger. A "fouling bar" is fixed on the track outside the running rails, which is erected when the signal is at danger and falls when the signal is at "clear." The arm is either interlocked mechanically with the signal itself or is operated by an air cylinder or electric motor. The trip cock is carried on the front coach of the train and consists essentially of a cock connected to the brake pipe, and having a long handle. If the fouling bar is erected this strikes it and opens the cock. The brake pipe is at once exhausted and an emergency application of brakes results Further the loss of brake pipe pressure causes the control governor to open and thus electric power is also shut off

An illustration of a trip-cock and fouling bar is shown in Fig 110.

For operation in either direction a trip cock must be placed on both sides of the train. English practice tends to supply one cock in a "set" or operative position on each end coach of a train on opposite sides, while the tendency in America is to put one pair on each motor coach. Under these latter conditions if

the signal returned to "danger" after the first coach or so had passed, the train would be tripped by the rear cocks, to obviate which a time lag relay is fitted to delay the erection of the fouling arm. The following tests may be of interest —

FIG. 110 —Trip Cock and Fouling Bar

A 6-car empty L N W.R. train travelling at 30 m p h. on level track in dry weather conditions pulled up in 238 ft , or roughly two-thirds of its own length, by the releasing of the Dead Man's Handle, representing a deceleration of 2·77 m p.h. per sec The time taken can be calculated as 10·8 secs. under these conditions The same train was then pulled up by the trip cock and as there is no control governor fitted, the application of brakes increased the load on the motors until power was cut off by the circuit-breakers falling out on overload. The train stopped in a distance of 336 ft., representing a deceleration of 1·95 m.p.h. per sec.

THE WESTINGHOUSE ELECTRO-PNEUMATIC BRAKE

The Electro-Pneumatic Brake has been designed in order to improve the Westinghouse Automatic Brake in some important particulars in which it falls short of the ideal brake, notably the following .—

(1) The "serial" action of the triple valves There is a time element elapsing between the operation of the triple valve on the first car and that on the last car, about 1½ to 2 seconds on a 6-car train. On long trains of 8 or 9 cars this time lag increases and becomes a serious matter, producing jerkiness of the stop owing to the rear cars still coasting while the front cars are braking, which naturally increases the stopping time.

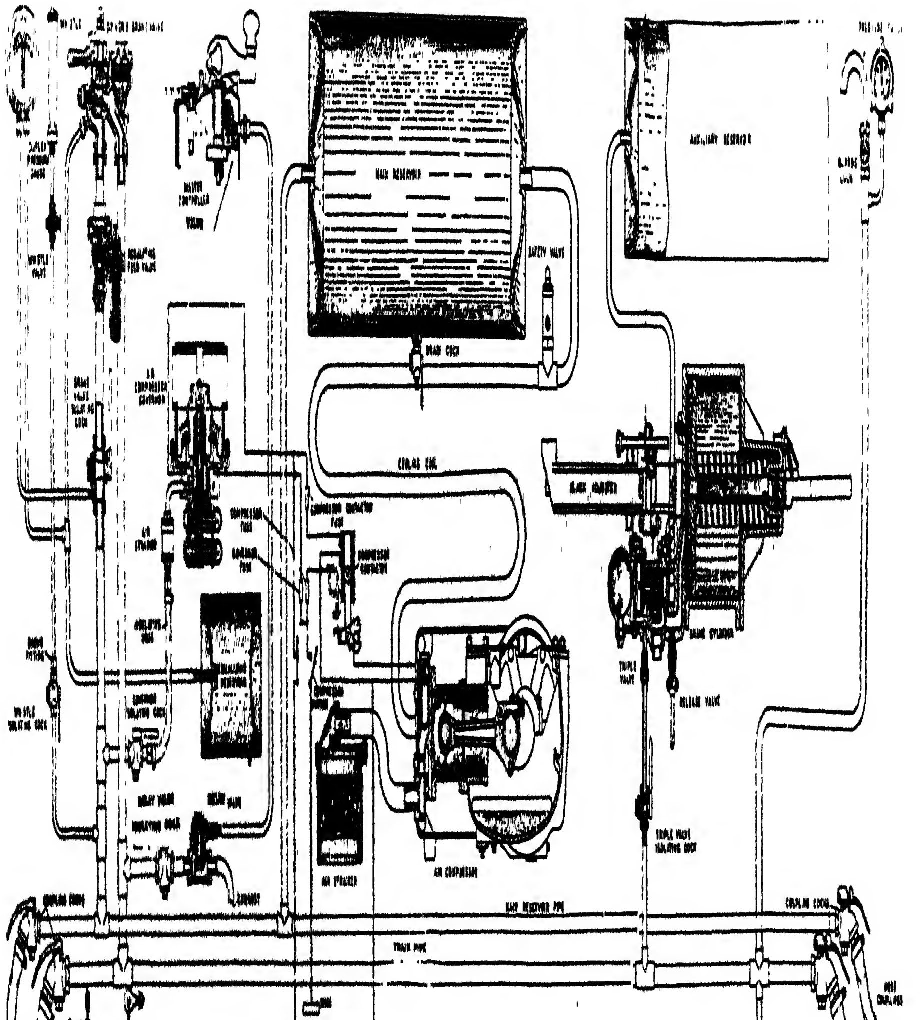


FIG. 100.—Diagram of Westinghouse Automatic Brake.

(2) The impossibility of graduating the release. If the brake has been applied with too much force, it cannot be eased off but must be completely released and re-applied. Theoretically too, a brake should be applied with greatest force at first, gradually easing it off as the train loses speed, if the train is to be stopped in the shortest possible time

The Electro-Pneumatic Brake, or "E P" Brake as it is called, removes these two objections entirely It is really an addition to the usual Westinghouse brake, the standard pneumatic apparatus being used, with the exception of the driver's brake valve, which is of a modified form, the usual equalising feature being dispensed with The E P. brake can therefore be applied to existing brake equipments without any radical alteration. Its principle, simply expressed, is that the supply of air to and from the brake cylinder is regulated by electrically-operated valves which act simultaneously on any length of train. The triple valves are not called upon to function at all except in the emergency position of the driver's handle Both application and holding valves can be opened and closed as often as desired, so that the pressure in the brake cylinder can be gradually increased or decreased, at the will of the driver, or it may be applied suddenly with full pressure in emergency. Since the supply of compressed air for the "E.P." brake is taken from the main air reservoir through a reducing valve, the ultimate brake cylinder pressure can be increased, within limits A higher braking force is therefore available than with the standard Westinghouse brake, and the graduated release allows this high power to be made full use of without the risk of skidding the wheels as the speed falls.

The electric features are interlocked with the air brake, so that a breakdown of the electric circuit of any kind, or on any car, when the driver's brake valve handle is in "Holding" or "Electric Application" positions, causes the triple valves to operate and apply emergency braking, after which the closing of a cock puts the electric features out of operation and allows the train to proceed using its standard Westinghouse brake equipment Thus the automatic and safety features of the brake are in no way impaired by the addition of electric apparatus. A small drum-type controller is provided for operating the brake, being mounted on the pneumatic brake valve, the spindle of which is coupled to the spindle of the controller drum.

Referring first to the wiring diagram, Fig. 111, it will be noted that each driving car has a source of current supply. This may be direct from the line for a 600-volt system (in which case resist-

ances are required for two of the magnets) or a motor generator, or other source of D C. supply at low voltage. The brake valve isolating cock at the driving end must be in the open position, and a switch attached to the cock provides that the correct electrical circuit to the interlock magnet is established All similar cocks on any other driving cars are in the shut position establishing the circuit as shown at the right-hand side of the diagram.

Position 1. The diagram shows the controller in the " Release and Running " position.

Current therefore flows from the supply contact on the controller to the third finger of the controller, through the interlock magnet on the driving car only, and back to negative. The interlock magnet is energised and its plunger is raised, thereby unseating valve A (Fig. 111) and allowing air to flow from the main reservoir pipe to the underside of the brake valve rotary but not into the brake pipe, the feed to the latter in this position being through a second port connecting the pipe immediately above the reducing valve with the brake pipe. The latter is therefore charged to the pressure to which the reducing valve is set, and the brake is in full release

Position 2. Passing now into the second or " holding " position, on making contact with the fourth controller finger and hence to the second train wire, current flows through the right-hand coil of the combined holding magnet and interlock switch on each car to the common negative. The plunger of this magnet is therefore moved, thus closing valve B, preventing the exhaust of any air previously admitted to the brake cylinder. It also closes the interlock contacts C which are in series through the train Current can now flow from the positive of the main switch to the fifth train wire, through the jumper dummy at the rear end of the train to the third wire, through the switch on the brake valve isolating cock, through all the interlock contacts in series, through the switch on the brake valve isolating cock at the driving end of the train, through the interlock magnet to negative. Thus, although contact to the third controller finger is broken, the interlock magnet remains energised provided all circuits are in proper working order. The direct feed to the brake pipe is cut off in this position, but a port in the rotary valve connects the interlock pipe with the brake pipe so that the feed to the latter is maintained.

Position 3. Passing to the third or " application " position, contact to the fourth finger is broken, but the second finger becomes energised and the application magnets of each car

throughout the train are energised, current passing through them, and through the left-hand coil of the combined holding magnet and interlock switch to negative, this coil (like the right-hand coil) moving the plunger and valve B, and closing the interlock contacts C, so that the interlock magnet is kept energised The energising of the application magnet lifts a valve D, which releases air from the top of the relay valve E, which accordingly lifts and allows air to pass from the main pipe direct to the brake cylinder The feed to the brake pipe is the same as in position 2

The longer the controller is kept on position 3 the greater will be the pressure in the brake cylinder Moving back to position 2 will hold the pressure in the brake cylinder, and as much or as little of this pressure as desired can be released by moving between positions 1 and 2.

Position 4. Position 4 is electrically the same as position 2 (holding), but the feed ports to the brake pipe are closed.

Position 5. In this position the driver's brake valve opens its service port and puts the brake pipe to atmosphere, causing the triple valves to operate and apply the brake as on a standard Westinghouse equipment. The holding magnets remain energised.

Position 6. In this position the holding magnets are de-energised and the application magnets again energised, air therefore flows to the brake cylinder from the main reservoir pipe. At the same time the pneumatic portion of the driver's brake valve is in the emergency position and rapidly exhausts the brake pipe to atmosphere which causes the triple valves to operate on each car

The safety features of the "E P." brake will now be clear. Should the supply current or any wire or connection fail, one or more holding magnets will drop out and its interlock contacts open, the result being that the interlock magnet becomes de-energised, and through its valve F allows air from the brake pipe to pass to atmosphere. The triple valves would then operate and brakes be applied automatically. If current cannot be restored, it is only necessary to close the interlock cut-out cock, thus shutting off connection between the valve of the interlock magnet and the driver's brake valve, and to operate the controller over positions 1, 4, 5 and 6 as a standard automatic Westinghouse brake.

A pressure gauge is provided to indicate the brake cylinder pressure, in addition to the usual duplex gauge.

The E P. brake becomes almost a necessity if rapid braking

on long trains is required. Its cost for a new equipment adds about 80 per cent to the total cost of the brake equipment, but the whole cost of brake gear for producing a high deceleration is small compared with that of the driving motors and electrical gear of the train whose object is the production of a high acceleration. Seeing that deceleration and acceleration are equally important factors if a high schedule speed is to be obtained, the cost of this highly efficient brake may prove a true economy, and it is noteworthy that it is being supplied for the Sydney Electrification.

The Vacuum Brake

A general arrangement of this brake is shown in Fig. 113.

In its simplest form this brake consists of a vertical cylinder (called the brake cylinder) fitted with a piston and piston rod, the latter operating the brake rigging through suitable levers A vacuum is maintained continuously on the top side of the piston, while air at ordinary atmospheric pressure can be admitted to or exhausted from the under side of the piston Under normal running conditions (i.e brakes "off") a vacuum is maintained on both sides of the piston, and the latter rests against the lower cylinder cover. When an application of the brakes is required, the vacuum is broken on the underside of the piston and the latter is forced upwards, thereby applying the brakes. The brakes are released either by recreating the vacuum on the underside or by equalising the pressure on the two sides This can be done as gradually as desired and the **Graduated Release** feature is thus seen to be inherent in this brake.

In practice each coach is equipped with a brake cylinder (in some cases two) which is connected to the train pipe as shown on diagram This pipe is continuous throughout the train and is connected to the operating (or driver's) valve on the locomotive or driving coach.

On electric trains the vacuum is maintained by a motor-driven exhauster or vacuum pump When the driver wishes to apply his brakes he moves the driver's valve over and thus allows a rush of air into the train-pipe throughout the train. The piston of the brake cylinder has now a vacuum above it and an atmospheric pressure on the underside. Thus it is forced upwards and the brakes thereby applied, the force of the application depending on the amount of air allowed to enter the train-pipe, i.e. on the extent to which the vacuum on the underside of the piston is destroyed, which can be read on a vacuum gauge placed in front of the driver

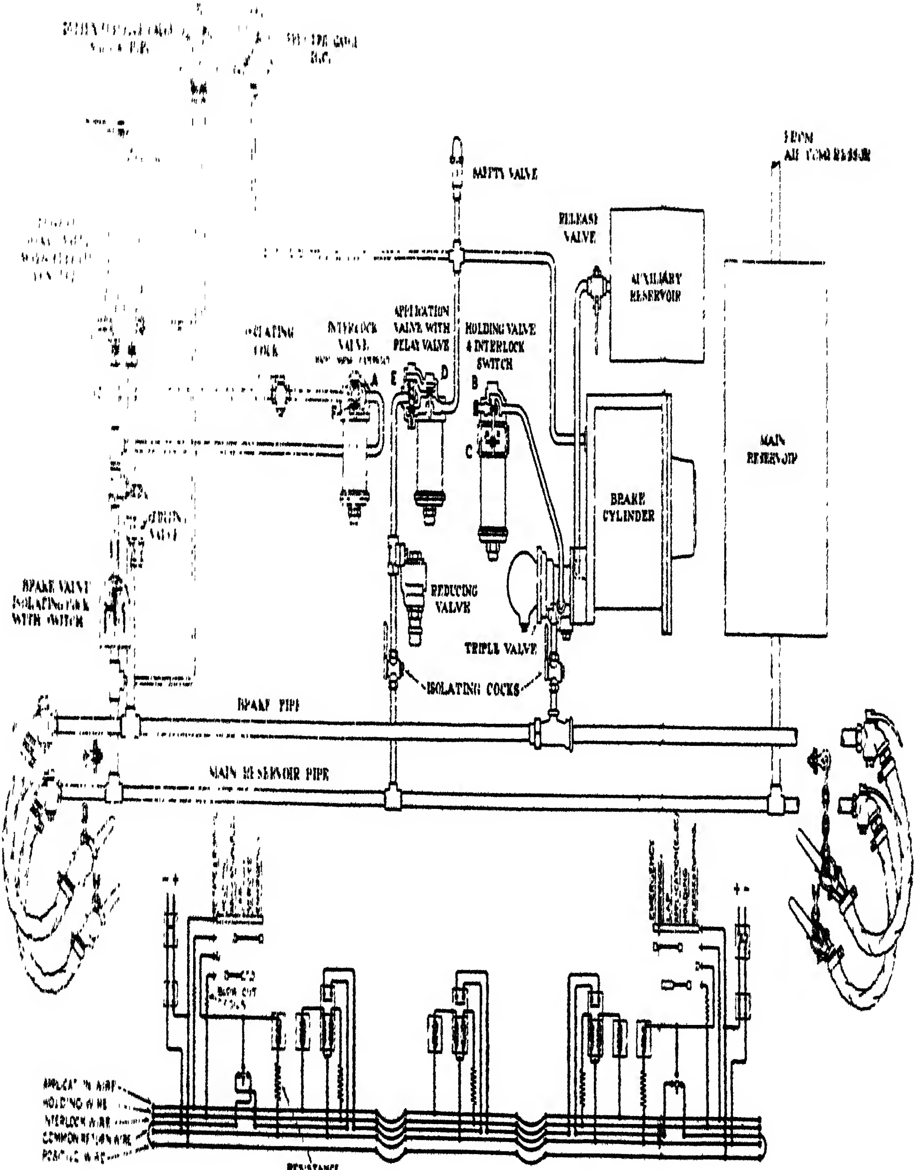


Fig. 111. Westinghouse Electro-Pneumatic Brake. General Arrangement and Wiring Diagram.

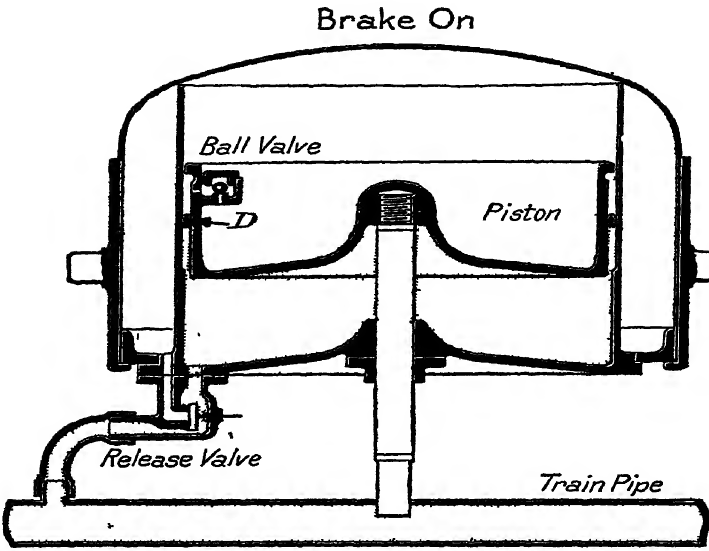
A driver's valve is placed in each driver's compartment and a guard's valve in each brake van A destruction of vacuum of 5 to 10 in. is all that is required for an ordinary service stop, and this should be re-created as the train comes to rest by placing the handle back into the "Running" position to avoid a jerky stop.

The **automatic action** of the brake becomes apparent when it is realised that accidental parting of the train or any damage to any part of the brake itself at once allows air freely into the train-pipe, causing immediate and automatic application of the brake with full power.

The exhauster is kept running continuously at half speed for maintaining the vacuum while the train is in motion. For quick release the exhauster is run at full speed On continuous current equipments the lower speed is obtained by inserting a rheostat into the motor circuit when the valve is in the "off" or release position. For single-phase A C equipments, two or more exhauster speeds for the exhauster motor can readily be obtained from tappings on the auxiliary transformer.

The extreme simplicity of the brake having been demonstrated, the various parts may now be considered in greater detail. Fig. 112 shows one type of brake cylinder. The cylinder is combined with and surrounded by the vacuum chamber which is provided with trunnions for mounting in a vertical position under the coach. The piston is an easy fit in the cylinder and is provided with a rolling rubber ring D, which when the piston moves rolls between it and the cylinder making a perfect packing without friction and preventing air leaking through from the underside of the piston to the vacuum above it. The piston rod is coated with brass, and works through a brass bush, and a rubber gland packing ring prevents air from passing the rod.

A small ball valve is placed over an opening leading to the upper side of the piston, and three small holes are drilled in the piston wall at the side of this valve immediately underneath the rolling ring. These holes make a direct connection between the train-pipe and the vacuum chamber space. When the exhauster is working, therefore, air is drawn out through the train-pipe and from the bottom of the piston direct; and from the top of the piston by way of the ball valve and small holes in piston. On applying the brake the air is admitted to the cylinder, when the piston at once moves upwards, causing the rubber ring to roll past the three holes, and thus cutting off all connection with the vacuum chamber The ball valve is not essential to the satisfactory working of the cylinder, but is fitted so that any air which



Position of Piston and Valve when a vacuum is created and the brake is off.

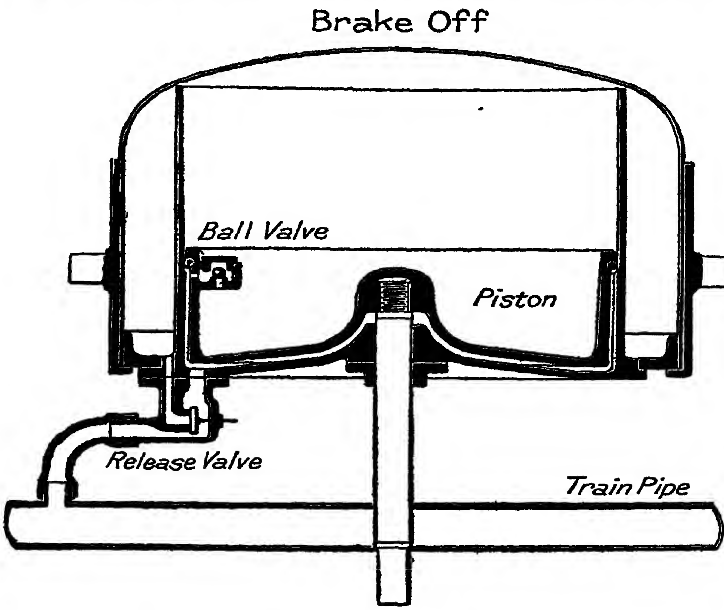


FIG. 112.—Cylinder of the Vacuum Brake.

Position of piston and valve when the brake is applied by the admission of air to the train pipe. The rolling ring preserves the vacuum on the top side of the piston, which is raised by the atmospheric pressure below it The dots indicate atmospheric pressure

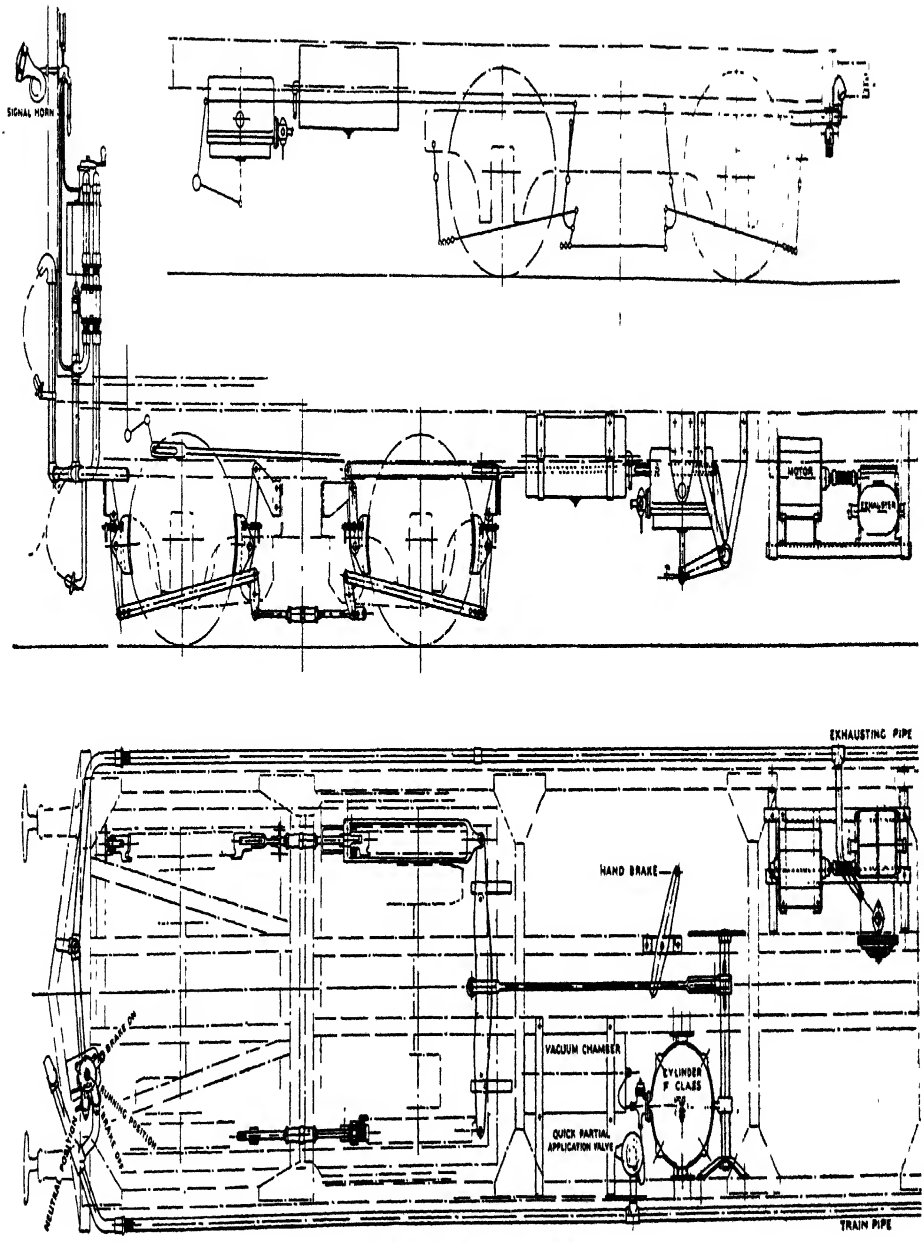


FIG. 113.—Vacuum Brake. General Arrangement.

may be carelessly admitted into the train-pipe or enter by leakage—but which is not sufficient to move the piston—presses the ball down on to its seat, and prevents the leakage from getting into the vacuum chamber and top side of the piston.

When for any reason it is desired to release the brakes on a particular coach by hand, the release valve is operated. This consists of a plain flat valve with rubber seating fitted over the hole leading to the vacuum chamber, the spindle, the body and cover Attached to this spindle is a diaphragm the outer edge of which is clipped between body and cap. To the spindle a lever is fitted to which a wire cord is fastened, running to each side of the coach When the cord is pulled the valve is removed from its seat allowing air into the vacuum chamber, equalising the pressures and releasing the brakes. When the vacuum is re-created in the train-pipe cylinder and release valve, the air from the outside forces the diaphragm, spindle and valve in again, automatically closing the valve.

On a long train there would be an appreciable interval after applying the brake before the air admitted could traverse the whole train line, and apply the brakes on the last coach. When a quick-acting brake is desired the brake cylinders are not connected directly to the train pipe but to auxiliary valves which are connected to the train pipe and to atmosphere.

Driver's Vacuum Gauges. The driver's vacuum gauge has two pointers—the one on the left marked " train pipe " and the one on the right " vacuum " chamber, both indicating the inches of vacuum On the application of the brake, the difference between the two readings, i e. between forces on each side of the piston indicates the amount of braking applied. For instance, if 10 ins is registered in the train pipe and 20 ins. in the vacuum chamber, the brake is applied with a power of about 10 ins. or about half its full power. The train-pipe should indicate at least 18 ins. continuously.

The motor exhauster is controlled by a governor, just as described for the Westinghouse brake, and is stopped and started at 20 ins. and 15 ins of vacuum respectively.

A modified form of this brake is in use on the Lancashire & Yorkshire Railway. The brake cylinder is fixed horizontally, and vacuum reservoirs are used by means of which the brakes can be released sufficiently rapidly to allow of 10-second stops being employed. This system is fully described in the paper of W. M. Hughes, *Proceedings of the Institution of Civil Engineers*, 1918–19.

At very high altitudes more trouble is likely to be experienced

from the reduced air pressure than with a compressed air brake. Some authorities state that the life of the rolling rubber packing ring is small in very hot climates, but in spite of all disadvantages the vacuum brake is a very good, simple and reliable brake.

Brake Theory and Brake Rigging

Co-efficient of Friction. As is well known, the so-called laws of friction state that the pressure applied normally between two surfaces and the resulting friction between them maintain a constant ratio, irrespective of load and speed. Thus if a body weighing 100 lbs. rests on a plane surface, and it is found that a horizontal force of 25 lbs. is required to move it, then the co-efficient of friction for these surfaces, usually called μ ("mu") is

$$\mu = \frac{\text{friction}}{\text{pressure}} = \frac{25\text{ lbs.}}{100\text{ lbs.}}$$
$$= 0{\cdot}25$$

The friction between a brake block and a wheel, however, is far from obeying these laws, as was shown by the classical investigation of Galton and Westinghouse, whose results were published in the *Proceedings of the Institution of Mechanical Engineers*, April, 1879.

The following table is given by them, and shows the variation of the friction co-efficient with speed for cast-iron brake blocks on steel tyres.

Speed Miles per hour.	Coefficient of Friction. Extremes observed Maximum.	Minimum	Mean
60	·123	·058	·074
55	·136	·060	·111
50	·153	·050	·116
45	·179	·080	·127
40	·194	·088	·140
35	·197	·087	·142
30	·196	·098	·164
25	·205	·108	·166
20	·240	·133	·192
15	·280	·131	·223
10	·281	·161	·242
7–5	·325	·123	·244
Under 5	·340	·156	·273
just moving	—	—	·330

The following table is given by Galton* and shows the variations in the co-efficient of friction with time.

Speed. Miles per hour.	Coefficient of Friction (C I. brake blocks on steel tyres).			
	First 3 seconds	5 to 7 seconds	12 to 16 seconds.	24 to 25 seconds
60	062	·054	048	·043
50	·10	07	056	—
40	·134	·10	08	—
30	·184	111	098	—
20	·205	·175	·128	07
10	·32	209	—	—
5	·36	—	—	—

The authorities named record without explanation the fact that the friction decreases with time. A series of elaborate tests made by the Pennsylvania Railroad Co in 1913 showed that the explanation lies principally in the high temperature produced at the actual contact face of the brake block, and the consequent softening of the metal which is being worn away. (N B. The discrepancy between the values of μ for a certain speed given in the two tables is explained by their being averaged from a different number of tests)

The first table shows clearly that the friction increases gradually as the speed falls, and increases quite sharply at rest

The term *Co-efficient of Static Friction*, or *Co-efficient of Adhesion*, is often used to denote the value of μ for surfaces which are not moving relative to each other ; and the term *Co-efficient of Dynamic Friction* for the case of surfaces which are relatively moving

The co-efficient of static friction is always the higher, and for this reason it is most important to avoid locking or skidding the wheels by excessive brake shoe pressure. While a car wheel is revolving its tyre surface is at rest with respect to the rail, and it may therefore be given a braking pressure just less than the product of the co-efficient of static friction × weight on the wheel. If this be exceeded and the wheel skids the brake shoes exert no braking effect, the contact surface is moving with respect to the rail, and the resistance to motion of the car is now the co-efficient of dynamic friction × weight on the wheel, a much lower figure than before. (Cf. Chapter XIV) Hence skidding the wheels is an inefficient way of bringing the car to rest, while the most efficient way, i.e. that which brings the car to rest in

*From Glazebrook's *Dictionary of Applied Physics*, Vol. I, p. 393. By permission of Messrs. Macmillan & Co.

the shortest possible distance, is to apply the highest pressure at the greatest speed, reducing it gradually as the speed falls, and keeping it throughout just below the force required to skid the wheels

Values of Co-efficient of Adhesion. The co-efficient of adhesion is greatest when the rail is dry and clean. It is least when the rail is moist or "greasy" as it is called, which occurs in humid weather or in the early morning; and it is considerably higher for a really wet rail. It is slightly affected by temperature, and the worst rail conditions, i e lowest adhesion, are found with a combination of low temperature and moist rail. The adhesion can be materially increased by the use of sand.

The following figures are in general use .—

Condition of Rail	*Coefficient of Adhesion. Per cent.*	*If Sand is used. Per cent*
Dry	25	28–30
Thoroughly wet	20	25
Moist or "greasy"	15	25

Theoretically, the co-efficient of adhesion should be constant irrespective of speed, since whatever the speed there is no relative movement between wheel and rail at the point of contact. Practically, however, the vibration and rolling at high speeds has the effect of reducing the load momentarily and so of reducing the adhesion, and this is taken into account in designing high-speed electric locomotives. Little has been published on the subject, although tests have been made to prove these conclusions, and no figures are available.

The co-efficient of adhesion is an important factor both for the starting and stopping of trains, since both operations depend on the application of a force to the wheels which must be just insufficient to overcome the adhesive friction

A steam locomotive, and to a lesser extent an A.C electric train, develops a pulsating torque, the maximum value of which is considerably higher than the mean; while for a direct current the torque is steady This allows of a relatively higher tractive effort on the D C. system, for the same weight of train, or a lesser weight for the same tractive effort.

A maximum co-efficient of adhesion of 25 per cent. is generally used in the design of electric trains, i e. the total tractive effort of the motors must not exceed 25 per cent. of the weight of the motor coach.

Braking Power and Brake Rigging Efficiency. From the foregoing considerations it will be realised that the maximum

brake pressure applied to the wheels must be proportioned to the weight on those wheels. In good modern electric practice the total pressure on all blocks is arranged to be about 110 per cent. of the tare (i.e. empty) weight of the motor coach ; and 90 per cent of the tare weight of the trailer coach. These figures are based on the full equalising brake cylinder pressure of 50 lbs. per sq. in. (The expression "brake power" is used where "brake force" would be more correct; but as the word "power" is in general use it would be pedantic to alter it.) In the form in which these percentages are given, it will be seen that the friction of brake piston, force of release springs and the general friction of the brake rigging have all been taken into account. If the brake power is calculated from piston pressure and overall leverage ratio, an overall efficiency figure of about 85 per cent. should be taken, to include for piston and rigging friction, and release springs

Brake blocks are usually of cast iron. Some railways use flanged blocks which are shaped to cover the flange of the wheel as well as the tread, while others prefer the smaller block, operating on the tread only There is also the Ferodo brake block, made of woven asbestos fabric,* which is much used on Tube railways. The co-efficient of friction for Ferodo blocks is very high (·56 to ·73) and the tyre wear much less than for cast-iron blocks, but if the train runs into the open air at any point, where the rails may be wet, these blocks cannot be used, since the co-efficient of friction when wet is very low indeed.

Blocks are sometimes applied to one side of the wheel only, but the best modern practice is to apply them to both sides of the wheel, and so avoid the large unbalanced forces on the bogie frame which result from single blocks.

The principle of the brake rigging is the use of a point on one moving lever as a fulcrum for another, so that all brake blocks are pulled up to the same pressure. A glance at Fig. 114 will make this clear. The force from the brake cylinder is transmitted through the pull rod A, which is connected to D, the centre point of BC The forces in BE and CM must therefore be equal even if, for example, owing to greater wear on one brake block, the point B should move one inch in the direction of A,

* By the use of the Ferodo block, the London Electric Railways have increased their braking rate to 3·4 m p.h. per sec., as against 2 m.p h. per sec. for cast-iron blocks. The life of the block is 16,000 miles, as against 8,000 for cast iron, and tyre wear 35,600 miles per $\frac{1}{16}$ in. radial wear, as against 7,000 with cast iron. The high deceleration permits of a longer coasting time with consequent economy.

and C move only half an inch. The pull on BE causes G to move round its pivot F until such movement pulls up G H and tightens up No. 1 block. Then G becomes the fulcrum and F moves, pulling up FI and swinging J round its pivot K until block No 2 is tightened. K and S are fixed to the bogie frame and are the only fixed points. The proportions of the levers are such that the two blocks are exerting equal pressures on the wheel An exactly similar process has been happening on the other wheel, and when A has pulled up all the slack the pressure on all blocks is equal

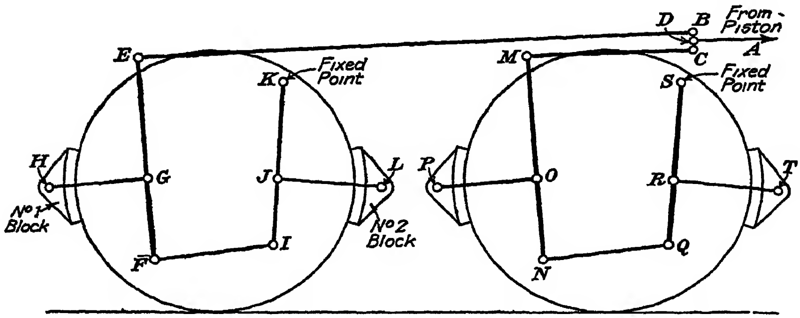


FIG. 114.—Brake Rigging Diagram.

Simple Brake Rigging Calculation. Fig. 114 shows in diagram the outline of a form of brake rigging, in which for simplicity the wheels on the other end of the axles are ignored. Let the brake pull rod A exert a force of 2,400 lbs. Then since D is the middle point of BC, the pulls in EB and in MC are 1,200 lbs. each.

EG = 15 ins.	MO = 12 ins.
GF = 10 ,,	ON = 8 ,,
IJ = 8 ,,	RQ = 8 ,,
JK = 12 ,,	RS = 12 ,,

(The dimensions correspond to the driving trailers of the L N.W R. stock)

EF, KI, MN, and SQ are levers, HG, JL, OP, RT, FI and NQ are tie rods, and the only fixed points on the system are K and S. All others are free to move.

Assuming pull of BE makes EF swing about F as fulcrum, then

$$\text{pull on HG} = \frac{\text{EF}}{\text{FG}} \times 1{,}200 \text{ lbs.} = \frac{25}{10} \times 1{,}200 = \textit{3,000 lbs. on Block H.}$$

When block H pulls tight, the lever EF swings about G as fulcrum, then

$$\text{pull on FI} = \frac{\text{EG}}{\text{FG}} \times 1{,}200 \text{ lbs.} = \frac{15}{10} \times 1{,}200 = 1{,}800 \text{ lbs.}$$

Since K is fixed, KI swings about K as fulcrum, then

$$\text{pull on JL} = \frac{\text{IK}}{\text{KJ}} \times 1{,}800 \text{ lbs} = \frac{20}{12} \times 1{,}800 = \textit{3,000 lbs. on Block L.}$$

Similarly pull on OP $= \frac{\text{MN}}{\text{ON}} \times 1{,}200$ lbs. $=$

$$\frac{20}{8} \times 1{,}200$$

$=$ *3,000 lbs on Block P.*

and pull on RT $=$

$$\frac{\text{MO}}{\text{ON}} \times 1{,}200 \times \frac{\text{QS}}{\text{SR}} \text{lbs} = \frac{12}{8} \times 1{,}200 \times \frac{20}{12}$$

$=$ *3,000 lbs. on Block T*

Thus the brake pressures on all blocks pull up to the same amount It will be noticed that the pulls may not always be at right angles to the levers, but the error involved is slight; and further the amount of wear on brake blocks and pins makes some difference to the actual brake pressures, so that the calculations shown are quite accurate enough for practical purposes. Where wheels of different diameters are used on the same train, the pressures on the blocks will be not equal but proportional to the load on each.

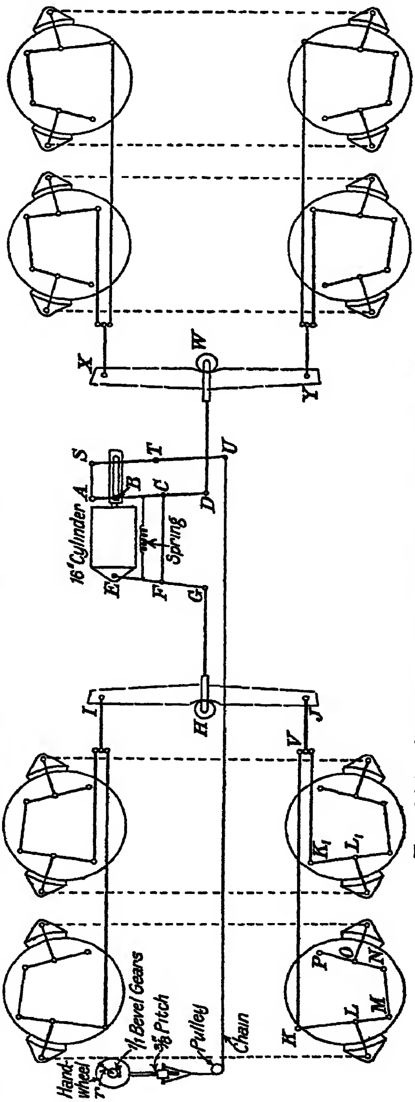


Fig. 115.—Complete Brake Rigging Diagram for Motor Coach.

Complete Brake Rigging Calculations. Fig. 115 shows in diagrammatic form opened out flat, the complete

brake rigging of an L N.W.R. motor coach, including the hand brake. GH and DW are the main pull rods connecting with the floating levers of each bogie. These levers (IJ and XY) are of considerable dimensions, on account of the large forces involved, and H and W are pulleys. The short lever V is horizontal so that KL and the corresponding lengths of levers on other wheels are equal, although they do not appear so on the diagram.

It will be noticed that B works along a slotted link so that when the hand brake is used B is able to slide along the link, being pulled from the point A by hand leverage, and the brake rigging is operated exactly as if the force were applied by the piston

Actual dimensions are as follows :—

EF = BC = $17\frac{3}{8}$ ins.	AB = 8 ins.
FG = CD = $16\frac{1}{8}$ „	ST = $23\frac{1}{8}$ ins.
KL = $K_1 L_1$ = $16\frac{1}{2}$ ins.	TU = $25\frac{3}{4}$ „
LM = $12\frac{1}{2}$ ins.	Diameter of cylinder = 16 ins
NO = $10\frac{1}{2}$ „	r = Radius of handwheel = 6 ins.
OP = 13 „	Pitch of handwheel screw = $\frac{3}{8}$ in.

The method adopted in these calculations is to compensate for the friction of the brake rigging, springs, etc., by assuming an equalising pressure of 50 lbs. per sq in. which is a little lower than the actual pressure.

Now at 50 lbs. per sq. in. equalising pressure, the total force exerted by the piston $= \pi \times 8^2 \times 50 = 10{,}000$ lbs.

$$\text{Force in pull rod DW} = \frac{BC}{CD} \times 10{,}000 \text{ lbs} = \frac{17\frac{3}{8}}{16\frac{1}{8}} \times 10{,}000 = 10{,}780 \text{ lbs.}$$

From the arrangement of levers it is evident that the force in pull rod GH is also 10,780 lbs.

This force will divide equally at I and J, and again at V, so that KV will be $\frac{10{,}780}{4} = 2{,}695$ lbs.

$$\text{Assuming M fixed, pull on L} = \frac{KM}{LM} \times 2{,}695 = \frac{29}{12\frac{1}{2}} \times 2{,}695 \text{ lbs} = \mathit{6{,}240\ lbs.}$$

$$\text{Assuming L fixed, pull on MN} = \frac{KL}{LM} \times 2{,}695 = \frac{16\frac{1}{2}}{12\frac{1}{2}} \times 2{,}695 \text{ lbs} = \mathit{3{,}555\ lbs}$$

$$\text{and pull on O} = \frac{NP}{OP} \times 3{,}555 = \frac{23\frac{1}{2}}{13} \times 3{,}555 \text{ lbs} = \mathit{6{,}420\ lbs.}$$

$$\text{Mean pressure on L and O blocks} = \frac{6{,}240 + 6{,}420}{2}$$
$$= 6{,}330 \text{ lbs. per block.}$$
$$\text{Total brake pressure (16 blocks)} = 16 \times 6{,}330 \text{ lbs}$$
$$= 45{\cdot}3 \text{ tons,}$$

which is $\frac{45{\cdot}3}{54{\cdot}75} = 83$ per cent. of tare weight (54·75 tons, *see* p. 231).

This figure is somewhat lower than the values obtaining in the latest practice, but it allows of quite satisfactory braking rates

The leverage ratio is

$$\frac{\text{the total brake power}}{\text{pressure developed by piston}} = \frac{45{\cdot}3 \times 2{,}240}{10{,}000}$$
(for the L N.W.R motor coach) = 10·1 : 1.

It should be mentioned that the brake blocks on opposite wheels are connected together by a rod as shown dotted in Fig 115

Hence the calculations above are usually expressed in formula form thus —

$$B = P \times 2 \times \frac{BC}{CD} \times \left\{ \left(\frac{KL}{LM} \times \frac{NP}{OP}\right) \times \frac{KM}{LM} \right\}$$

where B = total brake power, and P is piston pressure.

This formula is of course a condensed form of the calculations given. The formula will be different for each type of brake rigging, but can be readily evolved from the simple principle of levers in the same way as in the case calculated.

Hand Brakes. Each driving compartment (i.e. motor and driving trailer coaches) is fitted with a hand brake. The hand brake operates by means of a hand wheel, through bevel gearing to a screw, which pulling up its nut puts tension on a chain connected with a pull rod, connecting through levers to the main operating levers. T is fixed to the car frame. On applying the hand brake, the pull is applied at A, swinging the lever round C as fulcrum and pulling B forward along the slotted link, without moving the piston. Brake blocks are usually set to fall clear of the wheels by gravity, but a release spring is also applied to pull the brakes off after they have been applied by the hand brake. This spring is not necessary on trailer cars with no hand brake Assuming that the motor-man can exert a maximum force of 100 lbs then the leverage to the point B, i.e. the force which the piston would have

to develop to produce the same brake effect as the hand brake,

$$= \frac{100 \times 2\pi \times r}{\frac{3}{8}} \times \frac{\mathrm{TU}}{\mathrm{ST}} \times \frac{\mathrm{AC}}{\mathrm{CB}}$$

$$= \frac{100 \times 2\pi \times 6}{\frac{3}{8}} \times \frac{25\frac{3}{4}}{23\frac{1}{8}} \times \frac{25\frac{3}{8}}{17\frac{3}{8}}$$

$$= 16{,}350 \text{ lbs}$$

As found before the brake leverage ratio is 10·1 : 1

total brake power $\mathrm{B} = \dfrac{16{,}350 \times 10{\cdot}1 \times {\cdot}6}{2{,}240}$ (allowing for an overall brake rigging efficiency of 60 per cent.)

$$= 44 \text{ tons.}$$

(This efficiency is low because the bevel gears, spindle and screw friction, pulley and chain, etc , must all be accounted for as well as the friction of all the power rigging.)

Thus the hand brake power is seen to be some 97 per cent of the full power brake effect. It must be remembered that this brake can only be individually applied to each car on which it is fitted, but it is found sufficiently powerful to hold a 3-car train on any gradient if applied to the front car only

Braking Distances. The time in which a car can be brought to rest depends upon :—

(1) the maximum cylinder force,
(2) lapse of time before brake takes effect,
(3) efficiency of brake rigging, and
(4) co-efficient of friction.

The first three of these are controllable by design and can be estimated. To find, for example, the distance in which a train travelling at a certain speed can be stopped, we can equate the kinetic energy of the train to the total retarding force multiplied by distance travelled before coming to rest.

If initial speed be V m p h or v ft p. sec.
And brake force expressed as a fraction of weight of train $= p$
Average co-efficient of friction of blocks on wheels $= \mu$
Distance travelled from point of applying brakes to rest = D feet.
Dead weight of train empty = W tons.

Kinetic energy of train $= \frac{1}{2}$ m.v.^{2} ft. lb. $= \dfrac{\mathrm{WV}^2}{2g} \times 1{\cdot}47^2$ ft. tons

$$= {\cdot}0334 \,\mathrm{WV}^2 \text{ ft. tons.}$$

Work done in braking $= \mu p$WD ft. tons.
then μpWD $= \cdot 0334$ WV²

$$\text{whence D} = \frac{\cdot 0334\ V^2}{\mu p}$$

In this formula the rotary inertia and the normal train resistance during the braking period, which tend to cancel out, are alike neglected. If it be desired to include for both effects, the equation evidently becomes

$$\mu p\ \text{WD} + \frac{r}{2240}\ \text{WD} = \cdot 0334\ \text{WV}^2\ k$$

$$\text{whence} \qquad D = \frac{\cdot 0334\ V^2\ k}{\mu p + (r \div 2240)}$$

where k = ratio of effective weight to dead weight
and r = average train resistance in lb. per ton, during braking period.

Example. Find the braking distance of a L N.W.R. six-car train, travelling at 30 m p h. on level track, if emergency braking is applied.

The average value of p must first be found

Trailers and driving trailers have the same brake power which, as calculated on page 214, is 3,000 lbs per block. The total brake power is thus 16 × 3,000 lbs. = 21 45 tons per car. The total brake power for motor coaches, as shown on page 217, is 45·3 tons.

The total brake power for a 6-coach train, consisting of two of each type of car, is therefore 176·4 tons. Total weight of a 6-coach train is 224 tons.

$$\therefore \text{Average value of } p = \frac{176{\cdot}4}{224} = \cdot 788 \text{ (or 78·8 per cent).}$$

From the Galton table previously given (page 211) we can obtain a value of μ. For an average speed of 15 m p h. and for an average time of 5 seconds, μ will be ·2.

$$\text{Then} \qquad D = \frac{\cdot 0334 \times 30^2}{\cdot 2 \times \cdot 788} = 191 \text{ ft.}$$

If rotary inertia is allowed for (12 per cent), this becomes 1·12 × 191

= 214 ft.

and a correction for train resistance at 7 lbs per ton reduces it to 208 ft.

There is still one correction which must be made. In a 6-car

train there may be as much as two seconds time lag before the brakes are actually applied on the rear car, owing to the triple valves not operating instantaneously. Taking an average time lag of one second, the train travelling at 30 m p h. will have moved 44 ft , which must be added to the calculated figure. The overall braking distance is therefore 208 + 44 ft.

$$= 252 \text{ ft.}$$

Compare this with the 238 ft actually obtained by trial as mentioned on page 202. The closeness of agreement between trial and calculation in this case must be largely attributed to good luck, since so many factors of a highly variable character are involved. The example will serve, however, to convey an idea of the relative importance of these factors, and the general method of calculation

Supposing the train were loaded, e.g. with 24 tons of passengers, the weight would be 248 tons instead of 224, and the value of p would have to be changed to $\frac{224}{248} \times 78{\cdot}8 = 71$ per cent , which would considerably increase the braking distance.

If the braking distance is known, as in the case of an actual trial, the deceleration rate is calculated by the usual mechanical formulæ.

EXAMPLE. In the case of the above train, pulling up from a speed of 30 m p h. in 238 ft , to calculate the deceleration rate,

$v^2 = 2as$, in ft., lbs. and secs. units, becomes

$$V^2 = \frac{As}{{\cdot}733} \text{ where } V = \text{speed in m p.h.}$$

$$A = \text{deceleration in m.p h.p s.}$$

$$s = \text{space in ft.}$$

$$\text{i.e.} \qquad A = \frac{{\cdot}733V^2}{s}.$$

Hence, in our example $A = \frac{{\cdot}733 \times 30^2}{238} = 2{\cdot}77$ m p h. per sec.

Braking time. $V = At$, or $t = \frac{30}{2{\cdot}77} = 10{\cdot}8$ secs.

Compressors. For operating the air brakes, if of the Westinghouse type, an air-compressor is required, which is usually of the two-cylinder, single-acting, single-stage type, air cooled, driven by a small motor of some 5–10 horse power. Some direct-coupled compressors exist and are usual in locomotives, but for

use on motor coaches it is preferable to employ a moderately high-speed motor driving the compressor through double-helical gearing. The motor and compressor are built to form one complete unit which is usually suspended from the underframe of the coach The motor is of the series type for D C. working, while for A C the compensated-series or the repulsion motor is used

The two best-known types of compressor are the Westinghouse Brake Co 's "Bungalow" type, and the "C.P." type of the American General Electric Co. and B T H. Co

The "C P." type compressor usually employs a double-helical drive and is made in various sizes, of which the C P. 30 is the largest

Some dimensions and ratings of this size are given below .—

Bore of cylinders . . .	$5\frac{1}{2}$ ins
Piston stroke	7 ins.
Speed of compressor . .	188 r p m
Motor rating	$8\frac{1}{4}$ h p. at 1,060 r.p m.
Rated delivery	36 cub ft per min.
Actual delivery (when working continuously) . . .	27·25 cub ft per minute.

The rating of compressors is usually stated in terms of piston displacement, i e. the volume swept through per minute by the piston, and refers to free air, at atmospheric pressure. Thus in the case of the C.P. 30 compressor above, the volume displaced by the pistons will be

$$\frac{\pi}{4} \times 5{\cdot}5^2 \times 7 \times 2 \times \frac{188}{1{,}728} \text{ cub. ft. per min.} = 36 \text{ cub. ft per min.}$$

If the rating referred to the volume of air at a stated pressure, it is evident that the rating would need to be corrected for temperature and would vary with the pressure. With a rating in terms of free air drawn into the compressor the rating is constant for any delivery pressure and is unaffected by the temperature of the air delivered

The difference between the 36 cub. ft. per minute piston displacement and the actual delivery of 27·25 cub. ft. is due to the fact that a certain clearance volume is unavoidable and some air, compressed to maximum pressure, is therefore wasted There is also a loss due to a slight time element in the closing of the valves.

The volumetric efficiency in this case will be

$$\frac{27 \cdot 25}{36} = 76 \text{ per cent. (approx)}$$

Time required to Pump up a Train. An estimation of the time required for a given compressor to pump up the brake system of a train to service conditions can readily be made. It is assumed that at starting all reservoirs and pipes are at atmospheric pressure. In the case of the L. & N.W.R. 3-car train, the dimensions of the air brake system are as follows :—

Part.	Capacity in cubic inches		
	Motor	Trailer	Driving Trailer
Main reservoir	15,100	6,000	6,000
Auxiliary reservoir	6,000	3,013	3,013
Sanding reservoir	2,244	—	2,244
Equalising reservoir	487	—	487

These require sub-division into the Main system at 95 lbs. per sq in. and the Train system at 65 lbs. per sq. in as follows :—

Main System	*Cubic ins.*
Motor, Main Reservoir	15,100
Trailers, ditto. 2 @ 6,000 = . . .	12,000
Pipe line, estimated @ 5 per cent. of reservoirs = ...	1,360
Total	28,460

Train System.	*Cubic ins.*
Motor, Auxiliary Reservoir	6,000
Trailers, ditto. 2 @ 3,013 = ...	6,026
Motor and Control Trailer Sanding Reservoirs, 2 @ 2,244	4,488
Motor and Control Trailer Equalising Reservoirs, 2 @ 487 = ...	974
Pipe line, estimated @ 5 per cent. of reservoirs	875
Total	18,363

It is now necessary to determine the equivalent quantity of free air contained in these two systems at their respective pressures. Now a pressure of 95 lbs per sq in. is to be taken as gauge pressure, i e 95 lbs per sq in above atmospheric pressure which is approximately 15 lbs per sq in. A cubic inch of air at 95 lbs. per sq in (gauge) when expanded down to atmospheric pressure, i.e zero on the gauge (allowing time for the temperature to equalise), will occupy a volume proportional to the ratio of the absolute pressures, i e. $\frac{95 + 15}{15} = 7{\cdot}33$ cub. ins. Similarly for the system at 65 lbs per sq in the volume of 1 cub in becomes $\frac{65 + 15}{15} = 5{\cdot}33$ cub ins. These figures can therefore be used as equivalent correction factors, thus —

Volume of free air represented
by total Main system = 28,460 × 7·33 = 208,500 cub. ins.
Volume of free air represented
by total train system = 18,363 × 5·33 = 97,800 cub. ins.

Total equivalent volume of free air = 306,300 cub. ins.
= 177 cub ft

A C.P. 30 compressor having an actual delivery of 27·25 cub. ft. per minute will require $\frac{177}{27{\cdot}25} = 6{\cdot}5$ minutes to pump the train up to service pressure. This method ignores temperature correction altogether, but the compressed air in all reservoirs and pipes quickly cools to atmospheric temperature, and the times so calculated will be found to accord well with practice.

The starting current of a compressor motor may reach, at the moment of switching on, a value of over four times the running current, and the motor fuses must be liberally rated to withstand this momentary surge.

Compressor Governor. A governor is required to keep the air pressure within certain limits, to switch off the compressor motor when the main pressure reaches its maximum and to re-start it when the pressure falls sufficiently, the standard pressure range advised by the Westinghouse Brake Co being 75 to 95 lbs. per sq. in. The governor made by this Company employs a metal diaphragm having main air pressure on one side

and a spring on the other. A sufficient reduction of pressure causes a movement of the diaphragm sufficient to unseat a valve and liberate compressed air into a small cylinder, forcing up the piston which carries at its end a pair of electrical contacts, and thereby breaking the circuit. At the same time the exhaust air from the cylinder blows past the contacts and produces an effective air blow-out. The compressor motor, being series wound, can be started by the mere closing of the compressor governor switch, without starting rheostats.

Synchronising of Governors. Where two or more compressors supply air to a train at the same time it is usual to provide a synchronising wire, extending throughout the train, to ensure that all compressors start and stop together If this were not done, a compressor whose "cut in" pressure was fixed a trifle high would start up first and do all the work without allowing the others to operate at all. With the synchronising wire the closing of any compressor governor closes the circuit controlling all the compressors, which immediately start up until the same governor cuts out. Should two or more governors cut in together all the compressors will continue to work until the last governor (which will be that with the highest setting) cuts out It will be remembered that all the main reservoirs and pipes throughout the train are connected together so that the air pressure is practically uniform throughout the train. A simple diagram of connections for the synchronising wire is shown in Fig. 116

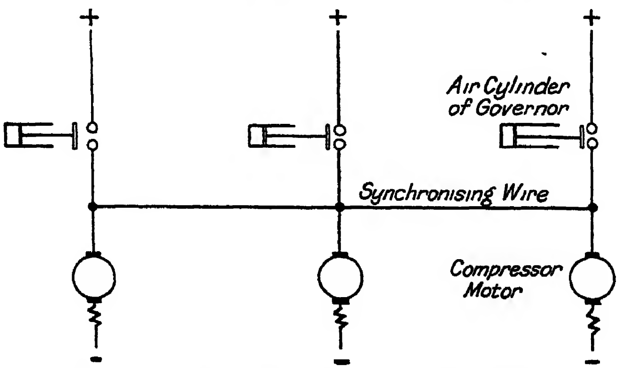


FIG 116—Compressor Synchronising Diagram

CHAPTER XI

TRAIN RESISTANCE

Components of Train Resistance. The term "train resistance" is generally defined as the sum total of all frictional resistance to the motion of a train moving at a uniform speed in still air on a straight and level track

The forms of friction are many in number and may be classified as follows :—

Sliding Friction Lubricated—friction of motor journals and wheel axles. Unlubricated—wheel flange friction and slipping.

Rolling Friction. Rolling of wheel on rail causing temporary deformation of surfaces, shock due to inequalities of surface.

Spring Friction Friction of all wheel and body springs, buffer and draw gear springs caused by rail joints, oscillation, etc.

Air Friction. Air friction at head of train, suction effect at rear, friction of air on roof, sides and underneath.

Track Friction. Elasticity of rails, sleepers, ties and track generally.

None of these can be computed with any degree of accuracy; further, the sliding friction varies roughly with the weight of the train and with the speed ; the air skin friction varies roughly as the square of the speed and is independent of the weight of the train, and the head and suction resistance are influenced by the shape of the ends of the train.

Any formula to include these variables therefore is likely to be of the form $R = a + bV + cV^2$, where R = total resistance in lbs., V the speed of the train in m.p.h , and a, b, and c are constants for any particular type of train, depending on journal friction, rail friction and wind resistance respectively.

Aspinall's Tests. The first classical tests for English passenger trains were made by Sir J. A. F Aspinall, on bogie coaches of the Lancashire & Yorkshire Railway. These tests were made with a steam locomotive and dynamometer car measuring

For example, the extra resistance for five L. & Y. coaches weighing 103 5 tons in all, length 257·4 ft. overall, will be at 50 m.p.h :—

$$(3{\cdot}2 \times 103{\cdot}5) + ({\cdot}065 \times 50 \times 257{\cdot}4) = 331 + 839 = \mathit{1{,}170\ lbs.}$$

The actual figures from Aspinall's tests show this to be 1,159 lbs, which gives strong confirmation of the closeness of this method of calculation. For *locomotive resistance* the New York Central

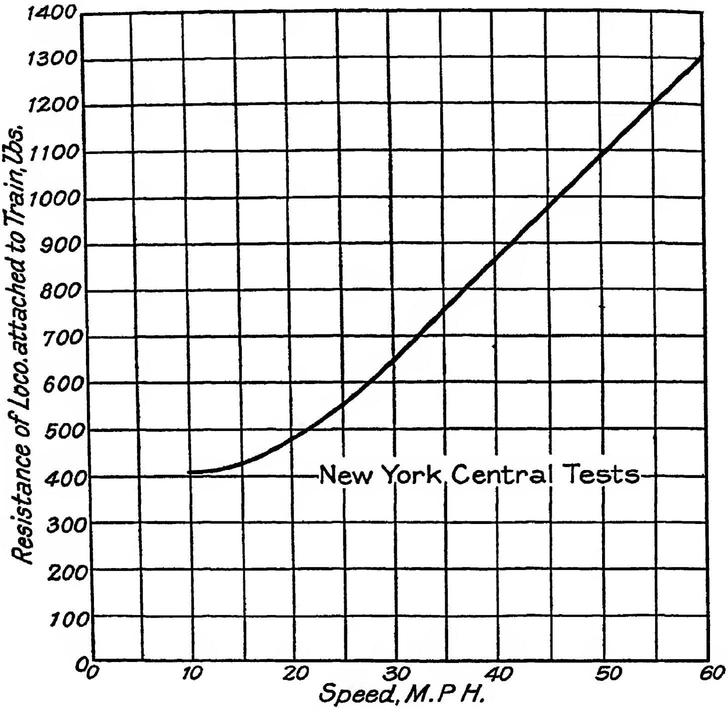


FIG. 119.

tests gave the curve shown in Fig. 119, which gives the resistance of an electric locomotive attached to a train (four-wheeled bogie coaches).*

Carter analyses this curve, and finds that the weight component is higher for a locomotive than for a coach, probably

* The resistance of a locomotive alone appears higher than that of a locomotive attached to a coach. Evidently the effect of a coach is to steady the running of the locomotive.

because of the depression of the road-bed caused by the higher load per wheel, and he writes the formula, corrected as before to suit English load gauges :—

R = 4 lbs. per ton + (·065 × speed in m.p h)lbs per foot length

In this curve and formula, head resistance is not included.

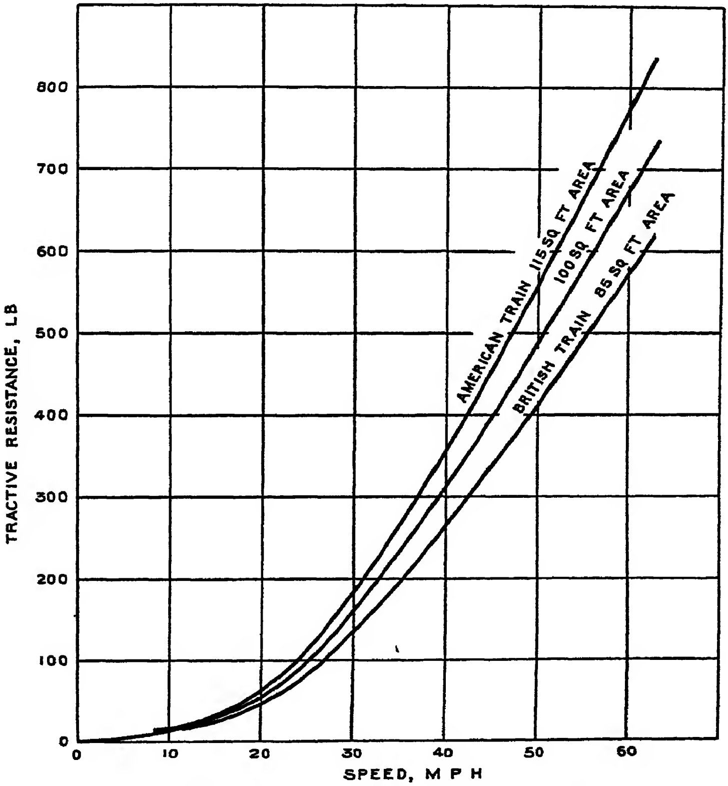


FIG 120.—Head Resistance, Train hauled by Locomotive.

Effect of Ends of Train. Having calculated the locomotive resistance and that of the additional coaches, there remains to account for the head (air) resistance, and rear suction effect to complete the calculations.

Fig. 120 shows the head resistance of an electric locomotive, the end suction effect being small enough to be neglected.

For multiple unit trains, the head resistance and rear suction

can be obtained from Fig 121. It is seen that, as would be expected, the shape of the ends considerably affects the head and rear resistances.

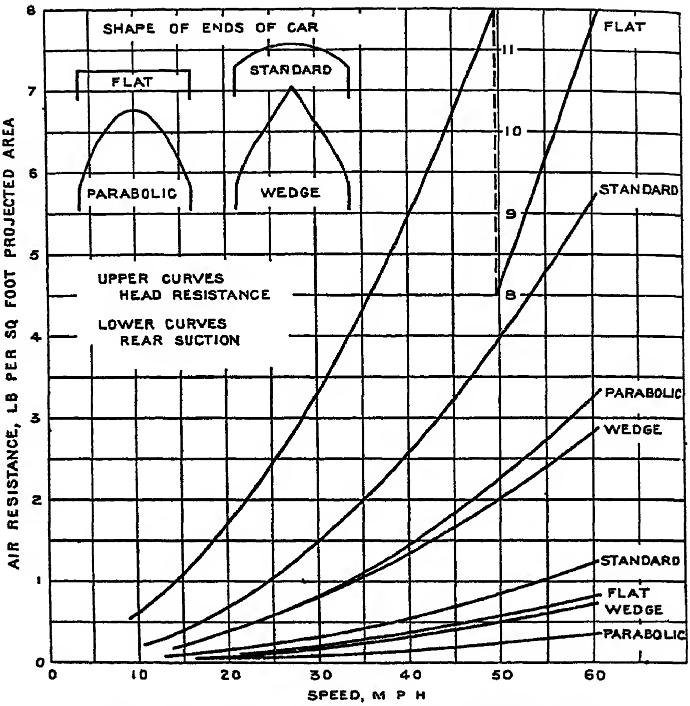


FIG 121.—Air Resistance. Louisiana Tests.

Carter's Method. This may be summarized thus :—

Resistance of Locomotive and Passenger Train

Resistance of locomotive = 4 lbs per ton + (·065 × speed in m.p h.) lbs. per foot length.

Resistance of each coach = 3·2 lbs per ton + (·065 × speed in m.p h) lbs. per foot length.

Head resistance, obtained from Fig. 121.

The sum of these will give the total resistance of the train.

Resistance of Multiple Unit Train.

(Treat motor coaches as locomotives)

Resistance of each motor coach = 4 lbs. per ton + (·065 × speed in m.p h.) lbs. per foot length.

Resistance of each trailer coach =

3 2 lbs. per ton + (·065 × speed in m p.h.) lbs. per ft length.

Head resistance and rear suction obtained from Fig. 121, using the curves appropriate to the shape of the car ends.

The under part of the car is to be treated as for flat ends, e.g. for a parabolic ended car the part above the floor line should be calculated from the "parabolic" curves, and the part below the floor line from the "flat" curves.

Resistance of Locomotive and Goods Train.

The resistance of goods wagons, particularly when loaded, is stated to vary but little with the speed, and the following table can be taken as substantially accurate between 5 and 30 m p.h. Starting resistance is about 10 lbs per ton.

Weight of loaded wagon	*Resistance*
17·8 tons	8·80 lbs. per ton
22·3 "	7 42 " " "
26·8 "	6 48 " " "
35·6 "	5 21 " " "
44·6 "	4·42 " " "
53·5 "	3 85 " " "
62·5 "	3 43 " " "
64·3 "	3 36 " " "

The formulæ given above for locomotives and added coaches apply to average English stock of a cross section of about 85 sq. ft., and if the cross section varies appreciably from this figure, the length component must be modified as explained previously.

The frictional resistance at rest may be taken as about 15 lbs. per ton in all cases, falling at 5 m p.h. to the figures given by the formula.

Example. The following shows the working out of this method for the 6-coach L N.W.R electric train for which we have already made so many calculations The train comprises two motor coaches each of 54·75 tons weight (empty); two trailers each of 28·225 tons, and two driving trailers each of 29·1 tons The trailers therefore average 28·66 tons each. The length of each car is approximately 60 ft.

Total weight of train is 224 tons.

Motor Coaches. R = 4 lbs. per ton + (·065 × speed in m.p.h.) lbs. per foot length.

Speed, m.p h	10	20	30	40	50	60
4 × 54·75	219	219	219	219	219	219
(065 × m p.h.) × 60 . .	39	78	117	156	195	234
Resistance for motor coach (lbs).	258	297	336	375	414	453

Trailer Coaches. R = 3·2 lbs. per ton + (065 × speed in m p h.) lbs. per ft length

Speed, m.p h.	10	20	30	40	50	60
3·2 × 28·66	92	92	92	92	92	92
(·065 × m p.h × 60)	39	78	117	156	195	234
Resistance for trailer coach (lbs.)	131	170	209	248	287	326

Head Resistance. These trains have flat ends, and the values from Fig. 121 are as follows :—

Speed, m p.h.	10	20	30	40	50	60
Head Resistance (lbs. per sq ft.)	·6	1 7	3 3	5 5	8·1	11·6
Rear suction effect (lbs per sq ft)	1	2	·25	·3	·6	·8
Head and rear (lbs. per sq ft)	·7	1 9	3·55	5·8	8 7	12·4
Total for 85 sq. ft. (lbs.)	60	162	302	493	739	1,054

Summing up we have :—

Speed, m p.h.	10	20	30	40	50	60
Two motor coaches	516	594	672	750	828	906
Four trailer coaches	524	680	836	992	1,148	1,304
Head and rear resistance	60	162	302	493	739	1,054
Total resistance of 6-car train (lbs)	1,100	1,436	1,810	2,235	2,715	3,264
Ditto, lbs. per ton	4 91	6·4	8 08	9·98	12·12	14·6

Although it is clearly incorrect to speak of train resistance in lbs. per ton as if it were a function of weight alone, the above results are shown plotted in Fig. 122 in the form of lbs. per ton for purposes of comparison Train resistance has similarly been worked out and plotted for 3- and 9-coach trains (although the L N.W.R. does not run 9-car trains) while for comparison the curve given by Aspinall and O'Brien for a 2-coach L & Y. train is also shown

Carter's method has the merit of being directly deduced from test results and modified to suit particular cases in a way not open to objection and can be applied to any type of train with

less likelihood of serious error than the usual application of formulæ expressed in lbs. per ton, derived from particular tests and applied generally.

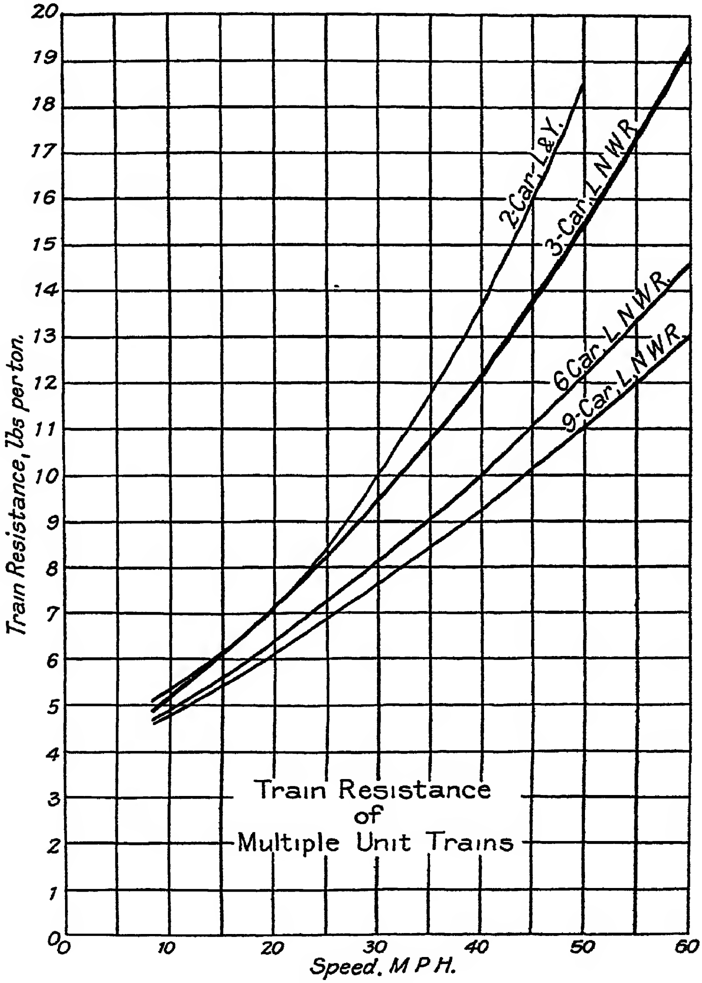


FIG. 122.

Two curves which may be of interest for comparison with the foregoing can be plotted from the following data :—

Speed, m p.h	0	10	20	30	40	50
Victorian-Railways (2-coach) lbs per ton . . .	15	5	5 5	10 6	14 5	19
New South Wales Railways (2-coach) lbs. per ton . .	—	5	7·15	9 91	13 4	17 7

The Victorian Railway curve was used in the specification for electric rolling stock prepared by Messrs. Merz and McLellan. The train consists of one motor and one trailer car, 5 ft 3 in. gauge.

The second curve has been adopted by the New South Wales Government Railways in their specification and is for one motor and one trailer car, standard 4 ft. 8½ in. gauge.

Armstrong's Formula. It may be advisable to give a formula for those who do not wish to use Carter's method. Of the vast number of formulæ for train resistance available, that of Mr. A. H. Armstrong is one of the best known and has the recommendation that it is used by the General Electric Co. (U.S.A) The formula is as follows :—

Resistance (in lbs. per ton of 2,000 lbs.),

$$F = \frac{50}{\sqrt{T}} + \cdot03V + \frac{\cdot002\ V^2A}{T}\left(1 + \frac{N-1}{10}\right)$$

where T = total weight of train in "short" tons of 2,000 lbs.

V = speed in miles per hour

A = cross sectional area of train, square feet.

= approximately 115 sq. ft. for American and 85 sq. ft. for British trains.

N = number of cars.

and $\frac{50}{\sqrt{T}}$ is to be limited to a minimum value of 3·5.

Mr. Armstrong states* that the formula applies more exactly to cars whose ratio of length to weight is about that obtaining in the United States, and that it will not be equally accurate for the shorter and lighter cars used in England and on the Continent.

Effect of Curves and Gradients. Curves increase the train resistance to an amount depending on the radius of the curve, the length of the fixed wheel base of the bogie, and amount of end play in wheel bearings. The sharper the curve the more the wheel flanges are rubbed against the rail, buffers together,

* Discussion on Carus-Wilson's paper, "Predetermination of Train

etc. Very little reliable data is available, and the matter is generally of no great importance in suburban working

A full working out of a number of formulæ by various authorities shows a fairly close agreement between them. One of the simplest is that by Dubois which, converted into British units, is as follows :—

$$\text{Resistance due to curve} = \frac{4{,}210}{\text{R}} \text{ lbs. per ton}$$

where R = radius of curve in feet.

The radius is measured, of course, to the centre line of the track rails. As the radius of a curve is often expressed in chains, this formula becomes $\frac{63{\cdot}6}{r}$ lbs. per ton

where r is the radius of the curve in chains (1 chain = 66 ft).

American practice generally expresses curves in degrees, i.e. the number of degrees of the angle subtended by a chord 100 ft. in length. A moment's consideration will show that if the angle given is a, then

$\text{Sin}\,\frac{a}{2} = \frac{50}{\text{R}}$, where R is the radius in feet, which works out to

$$\text{Angle in degrees} = \frac{5{,}730}{\text{R in feet}}.$$

This shows the method of converting from one system to the other. The formula above can be expressed in the American notation as approximately 0·8 lbs. per ton per degree of curvature but 0 9 lbs per ton is often used.

Another way of calculating the resistance due to curves is to say that the curve shall be taken as equivalent to a tangent gradient of 1 in 0·5 R, where R is the radius of the curve in feet This expression was found as a result of the Pennsylvania Railroad tests, and agrees very closely with the expressions given above.

Gradients It has already been stated in Chapter II that a train weighing W tons dead weight, on a gradient of 1 in n, is subject to a downhill pull due to gravity of $\frac{\text{W}}{n}$ tons or $\frac{2{,}240}{n}$ lbs. per ton.

or $\frac{22{\cdot}4}{\text{N}}$ lbs., where N is the percentage gradient.

In estimating train resistance over a given run the retardation due to curves must be added to the calculated resistance and

the gravitational pull added or subtracted according to whether the gradient is up or down.

Experimental Determination of Train Resistance. Since train resistance varies considerably with local conditions, it is often of use for the railway engineer to determine experimentally the resistance of his own trains on their particular track This may be done in two ways. (*a*) by measuring the input to the motors at various speeds and taking the corresponding tractive effort for each from the characteristic curve of the motor, or (*b*) by allowing the train to coast and calculating resistance from the retardation.

In the first method, the tractive effort of the motors is evidently entirely absorbed in train resistance if the train is moving at a uniform speed on level track, and the resistance is therefore the tractive effort.

The test is made more easily and accurately if no correction has to be made for acceleration and gradient, and various steady speeds can be obtained by cutting out motors, i.e. running with one, two, three or more motors pulling, and by running both in full series and full parallel. The readings at comparatively high currents are more accurate than at low currents, hence it is preferable to run with less than the full complement of motors. For great accuracy the characteristic curve of each motor preferably with its own gears should be measured separately on the test-bed either before or after the run.

The coasting test is commoner and is much more easily made. The train is brought up to speed and allowed to coast, the rate of fall of speed being measured, as for example in the experimental run curve for the L N.W.R train shown in Fig 24. The speeds at 40 and 50 seconds are respectively 29·4 and 28·3 m.p.h, i e the fall of speed is 1·1 m.p h. in 10 secs, representing a deceleration of ·11 m p.h. per sec. The dead weight of this train was 112 tons and the total effective weight 125·5 tons The train resistance is the force which produces this negative acceleration, hence $f = 102\ WA = 102 \times 125{\cdot}5 \times {\cdot}11 =$ 1,408 lbs., which is 12·6 lbs. per ton of dead weight This resistance then corresponds to the mean speed of 28·85 m p.h, and other values can be found for other speeds. The train resistance so obtained includes the friction of the motors and gears, which should be deducted if the true train resistance is required, and can be determined by driving the motor light from the wheel axle or on the equivalent shaft of the testing

The retardation can be measured directly at various speeds, by means of an accelerometer of the Wimperis pattern, in pounds

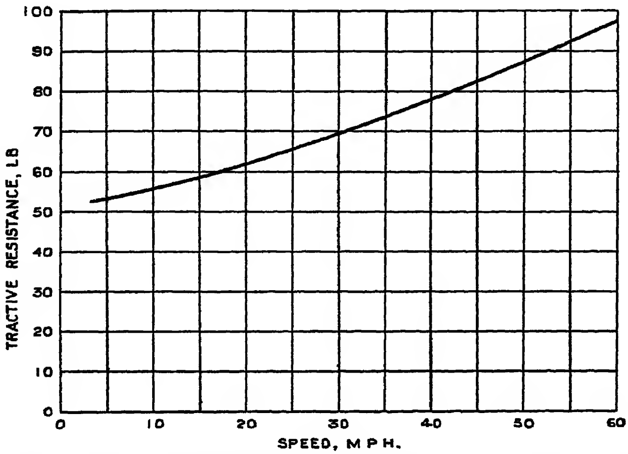


FIG 123.—Tractive Resistance due to 250 H.P motor with train coasting

per ton, and it must be remembered that this will represent pounds per effective ton, and the same correction must be made as before for friction of the motors and gears

Use of Train Resistance Curves. In estimating the average resistance between two speeds, the resistance should be taken as corresponding to a speed somewhat higher than the average speed, as shown on page 240.

CHAPTER XII

D.C. MOTOR PERFORMANCE AND RATING

Energy Consumption and Horse-Power of Motors. The energy output of the motors of a train up to the point of cut-off can be divided into :—

(1) Energy required to overcome train resistance.

(2) Energy required to accelerate the train

If the train resistance be r lbs. per ton, dead weight of train 1 ton, distance travelled up to the point of cut-off 1 mile, then work done against resistance will be 5,280 r ft.-lbs.

$$= \frac{5{,}280r}{33{,}000} \text{ horse-power mins.}$$

$$= \frac{5{,}280r \times 746}{33{,}000 \times 60} \text{ watt hrs.}$$

$$= 2r \text{ watt hrs. (nearly).}$$

Hence we may say that the motor output required is 2 watt hours per ton mile for every pound per ton of train resistance.

Now the total energy required to accelerate a train up to given speed is the kinetic energy of the train at that speed, which is $\frac{1}{2}mv^2$ in lbs., feet and seconds units.

If a train weighs 1 ton and the ratio of the total effective weight to the dead weight is k, then

Energy required for acceleration up to V m.p h.

$$= \tfrac{1}{2} \times \frac{k \times 2{,}240}{32{\cdot}2} \times \text{V}^2 \times \left(\frac{88}{60}\right)^2 \text{ ft.-lbs.}$$

$$= 74{\cdot}8\ k\text{V}^2 \text{ ft -lbs.}$$

$$= \frac{74{\cdot}8\ k\text{V}^2}{33{,}000} \text{ horse-power mins.}$$

$$= \frac{74{\cdot}8\ k\text{V}^2}{33{,}000} \times \frac{746}{60} \text{ watt hrs.}$$

$$= {\cdot}0283\ k\text{V}^2 \text{ watt hrs.}$$

... shown in Chapter II, k varies between 1·08 and 1·12,

i.e. total effective weight is from 8 to 12 per cent. above the dead weight.

If V be taken as the speed at which brakes are applied and n be the number of stops per mile (i.e. the number of times per mile the train must be accelerated from rest), then the whole output of the motors reckoned in watt-hours per ton mile on straight and level track is approximately $2 \times$ mean train resistance in lbs. per ton $+ \cdot 0283\ kv^2n$. The word approximately is used here because strictly speaking that part of the train resistance which continues throughout the braking period is not accounted for The error, however, is not great, and for a preliminary calculation of motor output, the expression given is of value as an estimate which can be simply and quickly made. Before deducing from it the electrical energy taken from the line, we must take into consideration the average efficiency of the train equipment which may be for continuous current motors operating on suburban systems about 80 per cent. A false efficiency of about 70 per cent. is often used to compensate for the up and down gradients met with in practice, track curvature, wind, accidental signal stops and the like, and where a fairly representative speed-time curve is available, based on level straight track, the formula given will give a reasonably accurate estimate of the energy required.

The efficiency figures given are intended to cover the motor losses, control and compressor energy and the rheostatic starting losses, but not of course the energy used for heating and lighting.

If no such speed time curve is available, it will be difficult to estimate the speed at the point of application of the brakes. Del Mar and Woodbury* have endeavoured to give greater precision to this calculation by using certain factors derived from experience. Their formula :—

Output of motors in watt hours per ton mile

$$= \frac{2}{Q} \times \text{(mean tractive resistance in lbs. per ton)} + \cdot 0283 k K^2 V^2 n.$$

where $Q =$ ratio of $\dfrac{\text{distance between stops}}{\text{distance travelled up to cut-off}}$

$K =$ ratio of $\dfrac{\text{maximum speed (at cut-off)}}{\text{average running speed}}$

$V =$ average running speed, excluding stops, in miles per hour

$n =$ number of stops per mile.

Q and K are to be obtained from the curves shown in Fig.

* *Electric Railway Journal*, Vol. 42, p. 1055.

124. The motor input, i e the energy drawn from the line, will then be obtained by dividing the result by the efficiency figure, in estimating which some allowance may be made for accidental stops, gradients and curves, as before.

In estimating the average train resistance it should be borne in mind that the average train resistance is greater than the resistance at average speed. A moment's consideration will make this clear, since for an accurate calculation of average train resistance a number of points on the speed-time curve

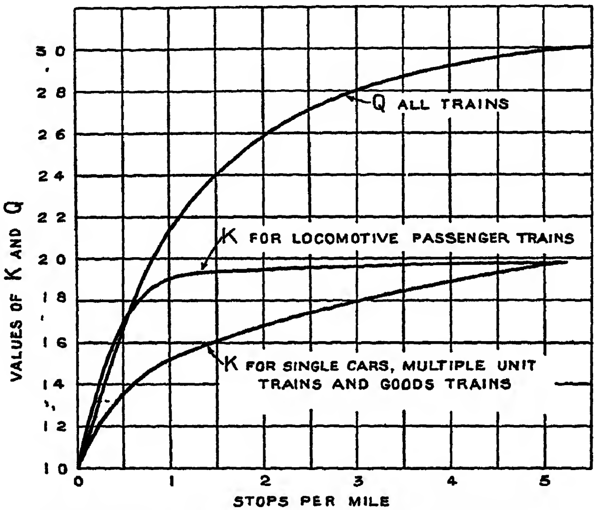


FIG. 124.—Del Mar and Woodbury's Factors.

should be taken, the actual resistance corresponding to them read off the appropriate curve (e g. those shown in Fig. 122) and the results averaged. Since the resistance-speed curve is not a straight line but a curve showing an increase of resistance more than proportional to speed, it follows that the higher values will preponderate in assessing the average, which will thus be higher than the resistance at average speed. As a practical illustration, if the mean running speed (excluding stops) is 30 m p.h., the mean train resistance should be taken to correspond to 35 to 40 m p.h., the higher figure being used for a considerable variation of speed from the mean.

In general it will be well to estimate average train resistance as corresponding to a speed of 10 to 20 per cent. above average

Corrections for Gradients :

If H_1 = sum total of rises of the track, in ft
H_2 = sum total of falls of the track in ft.
d = distance between stops in ft

Del Mar and Woodbury assume that only one-half the gravitational energy on down grades is saved, the remainder being consumed in the additional braking necessary To suit special cases variations of these proportions may be found necessary.

Then equivalent rise H ft. $= H_1 - \frac{1}{2}H_2$.

In a distance d ft , this represents an equivalent gradient of 1 in $\frac{d}{H}$, i e. 1 in G, where $G = \frac{d}{H}$.

The downhill gravity pull on 1 ton will be $\frac{2{,}240}{G}$ lbs.

Then energy per ton mile from motors while power is on

$$= \frac{2{,}240}{G} \times 5{,}280 \text{ ft.-lbs}$$

$$= \frac{2{,}240 \times 5{,}280 \times 746}{G \times 33{,}000 \times 60} \text{ watt hrs. per ton mile}$$

$$= \frac{4{,}450}{G}$$

Hence energy from motors over whole length of run to compensate for the effect of gradients $= \frac{4{,}450}{GQ}$ watt hrs. per ton mile, where G is the equivalent gradient and Q as before is the ratio of the distance between stops to the distance up to cut-off.

Correction for Curves. The average equivalent track curvature must first be found by multiplying each curve by its length; summing and averaging all such quantities and dividing by the total distance

For example, if a track of 2 miles length contains several 3-degree curves totalling 3,000 ft. in length and one 5-degree curve of 400 ft. length, the remainder being straight, the average equivalent curvature will be found thus :—

$$3 \times 3{,}000 = 9{,}000$$
$$5 \times 400 = 2{,}000$$
$$\overline{\underline{11{,}000}} \text{ degrees-ft.}$$

Total length $= 2 \times 5{,}280$ ft.

Average equivalent curvature $= \frac{11{,}000}{2 \times 5{,}280} = 1{\cdot}04$ degrees.

The train resistance due to curves was estimated (Chapter XI) at ·9 lbs. per ton per degree of curvature.

Hence resistance per ton $=$ ·9C where C is the equivalent curvature and energy from motors while running

$$= \frac{\cdot 9C \times 5{,}280 \times 746}{33{,}000 \times 60} \text{ watt hrs.}$$
$$= 1{\cdot}79C.$$

∴ Energy from motors over the whole length of run to compensate for curves

$$= \frac{1{\cdot}79C}{Q} \text{ watt hrs. per ton mile.}$$

EXAMPLE A suburban service is to be electrified and operated by 6-car multiple-unit trains on the D C system The average length of run between stations is 2 miles. The schedule specified is found to require an average running speed of 30 miles per hour. The average equivalent gradient is 0·05 per cent. and the average curvature 0·75 degrees An estimate is required of the energy consumption of the train in watt hours per ton mile

Estimate average train resistance at a speed 15 per cent. higher than the average running speed, i e. $1{\cdot}15 \times 30 = 34{\cdot}5$ m p h. The corresponding resistance from curve for 6-car train (see Fig 122) is 9 lbs. per ton. Equivalent gradient 1 in G where G $= \frac{100}{\cdot 05} = 2{,}000.$

There is one stop in each 2 miles, i e. number of stops per mile $n = 0\ 5$

Del Mar and Woodbury's constants, from Fig. 124, give the following :—

$$Q = 1{\cdot}67 \text{ and } K = 1{\cdot}36. \quad \text{Take } k = 1{\cdot}1.$$

Then, energy required for acceleration $= \cdot 0283\ kK^2V^2n$.
watt hrs. per ton mile.

$$= \cdot 0283 \times 1{\cdot}1 \times 1{\cdot}36^2 \times 30^2 \times \cdot 5 = 25{\cdot}9 \text{ (66·8 per cent)}$$

energy required for train resistance

$$= \frac{2}{Q} \times \text{average resistance}$$
$$= \frac{2}{1{\cdot}67} \times 9 \qquad = 10{\cdot}8 \text{ (27·9 per cent) ;}$$

energy required for gradients

$$= \frac{4{,}450}{GQ} = \frac{4{,}450}{2{,}000 \times 1{\cdot}67} = 1{\cdot}3 \text{ (3·3 per cent) ;}$$

energy required for curves

$$= \frac{1{\cdot}79C}{Q} = \frac{1{\cdot}79 \times \cdot 75}{1{\cdot}67} = 0{\cdot}8 \text{ (2·0 per cent).}$$

Total 38·8

To estimate the energy required for the line, an overall efficiency figure of 70 per cent. may be taken to cover the motor losses, rheostat losses and an allowance for energy to operate the control and compressor circuits

Then energy from line $= \frac{38 \cdot 8}{\cdot 7} = 55 \cdot 4$ watt hours per ton mile.

The energy figures are also shown in percentages for the sake of comparison. It is instructive to notice the relative amounts of each, and especially to note that the accelerating energy is some 67 per cent. of the whole. That expended on train resistance can alone be regarded as " useful " energy, so that the efficiency of the process so far as energy is concerned is just below 28 per cent , but efficiency of this kind must of course be sacrificed to save time, a higher efficiency representing a longer running time.

Predetermination of Motor Performance. The estimation of the horse-power required from the motors of a train for a given service is by no means a simple matter. The maximum horse-power is developed at the end of the straight-line acceleration period, since then the motors are carrying maximum current at full line voltage. This power rapidly falls off as the speed increases, since the rate of acceleration is reduced, and if power is left on until a steady speed is reached the horse-power will be that required to balance train resistance only. Since all traction motors are capable of heavy overloads for a short period, a motor whose rating is much below the maximum required will usually suffice for the service, the rating being actually decided upon from a consideration of the heating produced This in turn depends upon the copper and iron losses of the motor, radiating capacity, and the duty schedule which it is called upon to do

N W Storer, in the *Electric Journal,* 1908, gives the following method of determining the heating of a motor. The method consists in principle in running the motor on a testing stand at such values of current and voltage that the copper and iron losses resulting will be equal to the average copper and iron losses of the motor in actual service These values of current and voltage are called " equivalent heating current " and " equivalent voltage " respectively. The method will be readily understood from the following example :—

EXAMPLE :—

Track—level, 1 mile long

Train—Single car, 40 tons with load.

Schedule speed—24 m p h.
Motors—4 of 75 horse power.
Stops—1 per mile, 10 seconds each.
Average line voltage—500.
Acceleration—1·5 m.p h per sec.
Braking—1·5 m p.h. per sec.

The motor characteristics are shown in Fig. 125 and by using the ordinary point-to-point method of calculation described in Chapter III the speed-time curve is constructed as shown in Fig 126, on which are also plotted the motor current and voltage across its terminals to a time base from starting to stopping.

Equivalent Heating Current. The heating produced is of course proportional to the square of the current. The average copper loss is therefore proportional to the average of the squares of the currents over successive intervals. The current which, flowing continuously, will produce the same copper loss will be the square root of the average of the squares, i e. the equivalent heating current is the square root of the mean square current, generally known as the root-mean-square or r.m.s current. (It will be remembered that the average strength of an alternating current of any wave form is the r.m s. value)

In the example taken, the amperes per motor may be read off at 10-second intervals, the values squared and plotted. The area of the "current squared" curve so obtained is found, preferably by a planimeter, and averaged over the whole time including stops, i.e 150 secs , giving a r.m s. current of 56 amps This then is the equivalent heating current, and if the motor resistance is 0·184 ohms, the average copper loss is $56^2 \times \cdot 184 =$ 578 watts. The iron loss is calculated as follows: The current at starting is 134 amps. during acceleration At 200 volts this current gives an iron loss of 345 watts obtained from the iron loss curves for the particular motor shown in Fig 127; at 350 volts it is 750 watts and at 500 volts is 1,360 watts. At the end of 20 secs. the current has dropped to 68 amps , and full line voltage of 500 is on the motor. The corresponding iron loss is now 890 watts Other points are similarly found on the curve of iron loss plotted and averaged over the whole 150 secs , showing an average of 303 watts. The total average copper and iron loss is therefore $578 + 303 = 881$ watts. Evidently, therefore, to reproduce the service heating conditions on the testing bench we have only to run this motor at 56 amps., which gives the average copper loss, and at such a voltage as gives with 56 amps. an iron loss of 303 watts. This "equivalent

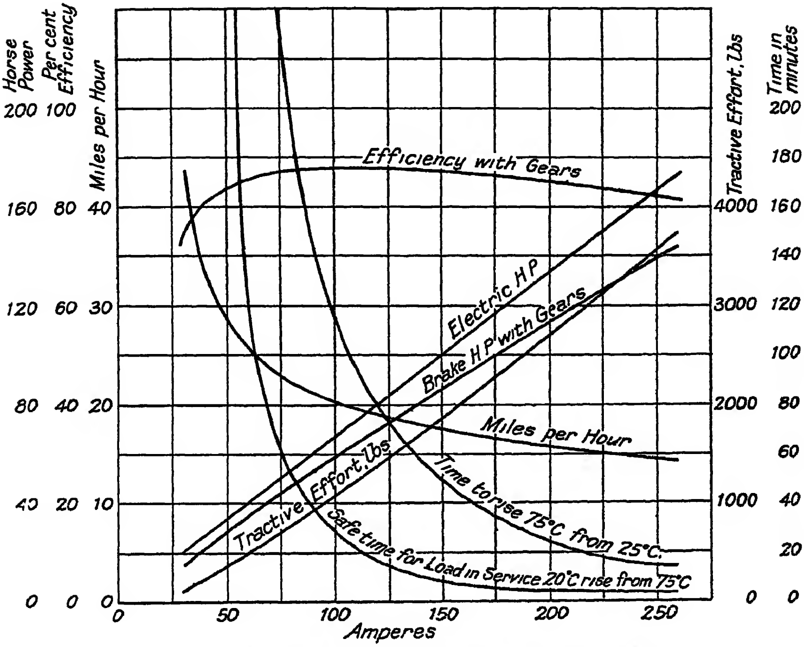


FIG. 125.—Characteristic Curves of a Railway Motor.

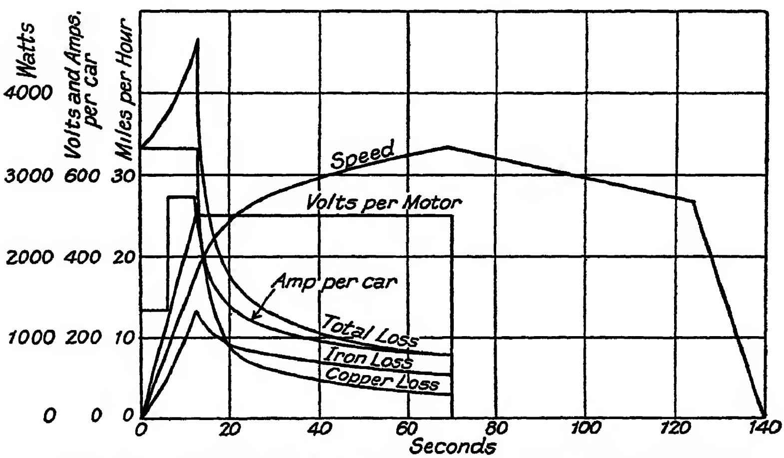


FIG. 126.—Curves of Speed, Current, Iron Loss and Copper Loss.

voltage " is found by reference to Fig 127 to be 290 volts As the allowable heating current of this motor at 300 volts is 60 amps. and at 400 volts is 55 amps., it is thus not necessary in practice to estimate the equivalent voltage very exactly. For average suburban working, a voltage of 300, i e three-fifths of the line voltage, will suffice, or four-fifths for longer runs where there is a smaller number of stops, producing a higher average voltage.

Since it is naturally undesirable to have to run an actual

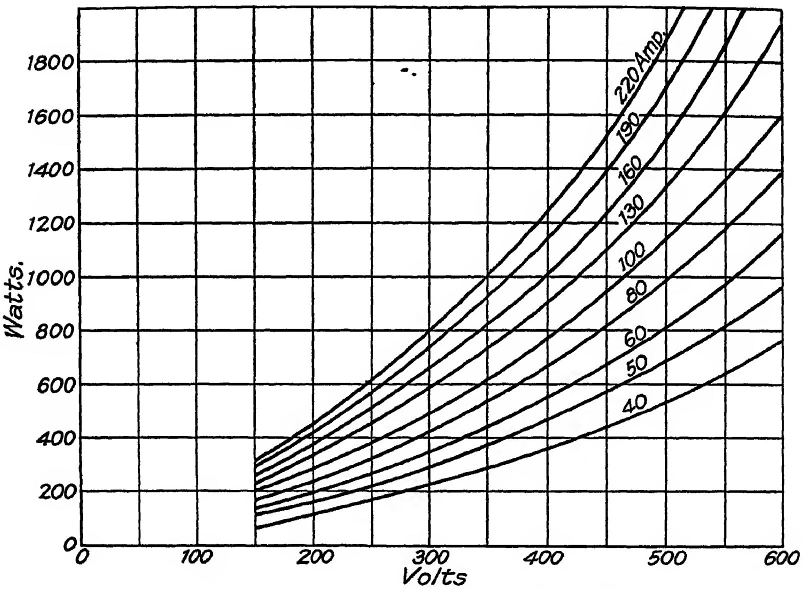


FIG. 127.—Iron Loss Curves of a Railway Motor.

stand test to estimate the heating of motors operating on a given service, heat dissipation curves are often supplied by the motor manufacturers, an example of which is shown in Fig. 128. If then the motor speed be averaged, the total watts lost per degree of temperature rise can be read off the curve and the actual motor temperature rise determined. If, therefore, a railway company is placing orders for traction motors, it is a wise precaution to obtain from the manufacturers in addition to the usual motor characteristic curve :—

(*a*) curves of iron loss plotted against current for several voltages, and

(*b*) a heat dissipation curve similar to Fig. 128.

The information is then to hand for the calculation of motor heating under any conditions, such as may arise when an accelerated service or heavier coaches are projected.

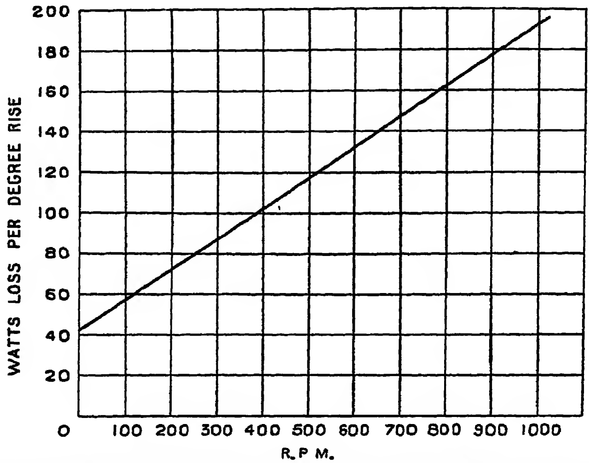


FIG. 128—G.E. 235 Railway Motor, Heat Dissipation Curves.

Rating of Motors. When a user wishes to instal a motor for driving a certain machine, factory or the like, he is usually able to determine to a fair degree of accuracy the horse-power which the motor will be expected to develop continuously. This horse-power rating is determined by the makers on a recognised basis of temperature rise and represents a very satisfactory indication of the capabilities of the motor.

In the case of most traction motors, however, there is no such steady and continuous duty, the motor operating normally in service through a series of quite irregular cycles, as follows :—

(1) A period of acceleration at heavy current and partial voltage

(2) A period of running at full voltage, during which the train accelerates with decreasing current.

(3) A period of running with power cut off but with full ventilation and the speed of the train slowly decreasing.

(4) A period of rest.

All of these periods vary with the length of run, schedule and stopping time, weight of train and gradients of the track. Now the temperature rise of the motor depends on the balance

of two opposing factors. (*a*) the rate of production of heat, i.e. the average power losses in the motor, and (*b*) the average heat dissipated; the former depending to some extent on the average voltage but still more on the root-mean-square of the current taken over the whole service, and the latter on the speed and ventilation of the motor.

One-hour Rating. Now the horse-power rating usually given to a traction motor is the one-hour rating, which is the horse-power which the motor will develop under steady standard conditions, producing a standard temperature rise after one hour The definition of this rating adopted by the American Institute of Electrical Engineers (A.I E E.) is more self-contained than the corresponding British Standard and is therefore more suitable for quoting for the purposes of explanation. The definition is as follows —

"The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90° C at the commutator, and 75° C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature, as measured by resistance, shall not exceed 100° C. The statement of the nominal rating shall also include the corresponding voltage and armature speed."

If this test were continued for a longer period the motor would reach a much higher temperature.

Continuous Rating. The continuous rating of a motor is the rating at which the motor will reach a steady temperature rise of the standard amount and will not exceed it if the run is continued indefinitely. A knowledge of this rating provides additional information for the comparison of motors

Now it is found that the loading required to heat a motor up to 75° C. in a one-hour run varies little whether the motor is arranged for free circulation of the outside air or is totally enclosed, for in the one-hour test run a very great proportion of the heat developed goes to heat up the whole mass of the motor. It is therefore evident that a thickening up of the metal inside the carcase or any other mere increase of mass, by adding to the heat-absorbing power of the motor, would increase the one-hour rating. As the heat-dissipating qualities of the motor would be unchanged, there would be no effect at all upon the

final temperature after a long run, and in some cases no effect on the service capacity.

If, on the other hand, the heat-dissipating qualities of the motor are improved by improving the air circulation through the motor, then the service capacity will be increased. It is therefore evident that there is very little relation between the nominal (or one-hour) rating and the service capacity, an illustration of which is the fact that the one-hour rating of the motors offered in the tenders for the Sydney electrification varied between 225 horse-power and 400 horse-power The service requirements were specified very fully and the calculations made by the tenderers, all of whom were firms of the highest standing, were very elaborate and detailed. There is no doubt that all the motors offered were of the requisite service capacity and equally certainly an unduly large margin would not be provided in a competitive tender for a contract of such magnitude. The figures are therefore entirely comparable.

The railway engineer who is called upon to examine a number of tenders for traction motors for a given service will attach no particular significance to the nominal rating; the suitability of a motor for a specified service must be considered in conjunction with the particular gear ratio with which it is recommended, while the nominal rating is an individual property of the motor apart from its gear; further, the overload capacity of a motor for short periods is limited rather by its commutating qualities than by heating, so that here again a high nominal rating is not necessarily an advantage Financial considerations apart, features of design, low weight, low gear speed and the like will be considered to be of greater importance than a high nominal rating.

Appendix III of the British Standard Specification for D.C. traction motors (1923) is a concise statement of the facts* :—

"NOTES ON THE RELATION BETWEEN TESTS ON TRACTION MOTORS AND THEIR TEMPERATURES IN SERVICE.

"The conditions of service of traction motors differ so much from those which govern ordinary commercial tests that the results of these tests are of little value as indicating the service capacity of a motor. The ratings accordingly have little absolute

* This and the following extracts from British Standard Specification, No. 173, 1923, are reprinted by permission of the British Engineering Standards Association, from which official copies of the Specification can be obtained, price 1*s.* 2*d.* post free.

value, and have relative value only when comparison is being made between motors of similar construction.

"The temperature rise under various conditions is dependent chiefly upon some or others of these several factors:—

(a) The *average* power loss in the motor.
(b) The power loss in the motor *at its final temperature*
(c) The capacity of the motor for heat (storage)
(d) The ability of the motor to dissipate heat
(e) Initial temperature of motor.
(f) Ambient temperature of cooling air

"Temperature rise depends chiefly.—

In the one hour rating test, on (a), (c) and (e);
In the continuous rating test, on (b), (d) and (f);
In service, on (a), (d), (f) and to a lesser extent (c).

"The temperature rises specified in the rating tests are not intended to have reference to service.

"In particular it may be noted that the rise specified in the one-hour rating test makes no distinction between classes of insulation, this being beside the purpose of the test

"The temperature attained in service is influenced not only by the characteristics of the motor and the nature of the service, but also by the nature of the road, height above sea level, and climatic conditions.

"It accordingly depends principally on the power-loss in the motor, on the ability of the motor to dissipate heat, on the ambient temperature, and, to a lesser extent, on the capacity of the motor for heat The several factors are continually varying and their effective values cannot be identified, even approximately, with any rating.

"The maximum temperature ordinarily permissible in service depends principally on the kind of insulation used and is variously estimated. It is, however, not generally considered objectionable if the limit is occasionally exceeded for short periods, on account of unusual circumstances, such as extreme ambient temperatures"

The following definitions are also found in the British Standard Specification:—

Nominal One-hour Rating Test (Clause 14). "The nominal one-hour rating of a series traction motor shall be the mechanical output in horse-power at the car or locomotive axle* at rated voltage and uniform current input which the motor is

*In accordance with a recent decision of the International Electrotechnical Commission, the output is in future to be measured at the motor shaft.

capable of providing for one hour, without exceeding the limits of temperature rise given in Section IV when tested under the conditions of Clause 24."

Clause 24 reads as follows :—

Nominal One-hour Rating Test. "For the purpose of this test the motor shall be run at its nominal one-hour rating, for one hour, on a test bed, with the covers (if any) arranged to secure maximum ventilation without external blowers. In the case of a motor in which the excitation can be varied independently of armature current, it shall be carried out under the conditions of maximum rated output. The initial temperature of the motor shall be approximately that of the surrounding air, and the temperature rise at the conclusion of the test shall not exceed the values given in Table 1."

Table 1 referred to above is as follows :—

Limits of Temperature Rise Permissible. "The temperature rise of traction motors when tested at the nominal one-hour rating under the conditions specified in Clause 24 shall not exceed the limits given in Table 1, whatever the class of insulation.

TABLE 1.

Item No	*Part of Machine*	*Temperature Rise measured by Thermometer*
1	Any accessible part of the Windings . . .	75° C.
2	Commutators	90° C.

Continuous Rating Test (Clause 15). "The continuous rating of a series traction motor shall be defined by the input in amperes at which it may be worked continuously at one-half, three-quarters and full rated voltage respectively, without exceeding the limits of temperature rise given in Section IV when tested under the conditions of Clause 25

"NOTE —Since the same motor may be worked under different conditions as regards ventilation, it is necessary in each case to specify the system of ventilation which is used, and in the case of motors cooled by external air blowers, the flow of air on which the rating is based should be specified. In all cases the rating shall include a statement of the corresponding armature speed and percentage of maximum field excitation"

Clause 25 reads as follows :—

Continuous Rating Test "For the purpose of this test the motor shall be run at its continuous rating, on a test bed, with motor covers and cooling system (if any) arranged as in service, until sufficient evidence is available to show that the maximum temperature rise when measured by thermometer would not

exceed the values given in Table 2 if the test were prolonged until the final steady temperature were reached. In the case of a motor in which the excitation can be varied independently of armature current, unless otherwise specified the continuous rating test shall be carried out under the conditions of maximum rated output "

Table 2 referred to above is as follows :—

" The temperature rise of traction motors when tested for continuous rating under the conditions specified in Clause 25 shall not exceed the limits given in Table 2.

TABLE 2.

Item No.	Part of Machine	Temperature Rise measured by Thermometer	
		Class A Insulation	Class B Insulation
1	Insulated Windings and Cores in which they are embedded .	65° C.	80° C
2	Commutators	85° C.	85° C

The Class A and Class B insulation referred to above are as follows :—

Classification of Insulating Materials. " Insulating materials are classified in the following way :—

" Class A. Cotton, silk, paper and similar materials when impregnated or immersed in oil, also enamelled wire.

" Class B Materials such as micanite and built up mica composed of mica splittings with binding cement, also asbestos. If Class A material is used in conjunction in small quantities for structural purposes only, the combined material may be considered as Class B, provided the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class B material. (The word 'impair' is here used in the sense of causing any change which could disqualify the insulating material for continuous service.)

" NOTE.—Impregnated Cotton, Paper and Silk. An insulation is considered to be 'impregnated' when a suitable substance replaces the air between its fibres, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substance, in order to be considered suitable,

must have good insulating properties ; must entirely cover the fibres and render them adherent to each other and to the conductor ; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause ; must not flow during the operation of the machine at the highest temperature limit allowed by this Specification for impregnated materials ; must not deteriorate under prolonged action of heat."

Clause 17 reads as follows :—

Commutation "A direct-current series-wound traction motor shall work in both directions of rotation with fixed brush setting practically sparklessly and without injury to the surface of the commutator or brushes from no load to the one hour rated load, and without injurious sparking or injury at a current not less than 30 per cent. in excess of the one-hour rated load current. The excess current shall not be applied for more than two minutes"

Clause 18 reads as follows —

Efficiency. "When a statement of efficiency is required, it shall be quoted on the basis of direct measurement, as laid down in Clause 26, at a temperature of 75° C, and not on the basis of summation of losses.

"NOTE —It shall be stated at the time of the inquiry whether the efficiency is to include or exclude the losses due to the gearing"

Clause 19 reads as follows :—

High Voltage Test. "The high voltage test shall be applied only to a new and completed traction motor in normal working condition with all its parts in place, and, unless otherwise agreed, shall be carried out at the maker's works at the conclusion of the one-hour test of the motor The motor shall have been exposed to the ordinary atmosphere for at least twenty-four hours prior to the temperature test

"It is generally advisable that the high voltage test shall not be applied when the insulation resistance is less than that indicated in Clause 20.

"An alternating high voltage of 1,000 volts plus twice the line voltage with a minimum of 2,000 volts (R M.S.) shall be applied for one minute between the windings and the frame of the machine"

Clause 20 reads as follows —

Insulation Resistance. "The insulation resistance in megohms, when the high voltage test is applied, shall be not less than

$$\frac{\text{Line Volts.}}{1{,}000 + \text{Rated Output in BHP}}$$

"Insulation resistance in megohms appreciably higher than the value obtained from the formula given above should not be specified for electrical machinery, since, in order to obtain it, long baking at high temperatures may be necessary, and this may permanently damage the insulating material.

"In drying out windings which have been exposed to damp for a long period, fictitious values of insulation resistance are often obtained when only a portion of the insulation has become dry, the insulation as a whole being still in a dangerous condition

"In drying out such windings it is therefore necessary to ensure, by long continued careful drying, that the insulation resistance shall actually reach a stable value of the required magnitude before the high voltage test is applied"

Clause 26 reads as follows :—

Efficiency Tests "The efficiency if required (*see* Clause 18) shall be directly measured, as for instance by the brake test, or by Hopkinson's test. This efficiency shall be corrected to a temperature of 75° C."

Clause 27 reads as follows :—

Test for Rated Speed "The rated speeds shall be tested at the rated loads, at the end of the nominal one-hour rating test, and shall not differ from the declared speeds by more than 3 per cent."

The following is taken from the Standardisation Rules of the American Institute of Electrical Engineers :—

Calculation for Comparing Motor Capacity with Service Requirements

"The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilised as follows to determine its temperature rise.

"The motor losses which affect the heating of the windings are, as stated above, those in the windings and in the core The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows :—

"(*a*) Plot a time-current curve, a time-voltage curve, and a

time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

"(*b*) If the calculated r m s service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

"(*c*) If the calculated r m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r m s. current, will produce the average core loss. Having obtained this, determine, as follows, the temperature rise due to the r.m s service current, and equivalent voltage

$$\left.\begin{aligned}\text{Let } \theta &= \text{temperature rise}\\ p_o &= \text{I}^2\text{R loss, kw.}\\ p_c &= \text{core loss, kw}\end{aligned}\right\}\ \text{with r.m s service current, and equivalent service voltage}$$

$$\left.\begin{aligned}\Theta &= \text{temperature rise}\\ \text{P}_o &= \text{I}^2\text{R loss, kw}\\ \text{P}_c &= \text{core loss, kw.}\end{aligned}\right\}\ \text{with continuous load current corresponding to the equivalent service voltage.}$$

Then :—

$$\theta = \Theta \frac{p_o + p_c}{\text{P}_o + \text{P}_c}, \text{ approximately.}$$

"(*d*) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one-hour test starting at ambient temperature.

"(*e*) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r m s. service current and equivalent voltage The excess loss, divided by the coefficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m s service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

"(*f*) If the temperature reached, due to the peak loads, does

not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle"

Some further details of the tenders for the Sydney motors may be of interest and are tabulated below. It is seen that no consistent relation exists between weight and horse-power and no simple means of comparing the relative suitability of motors for the specified service The standard specified was the American A I E E

Maker	(One-hour) Nominal Rating horse-power	Speed at 1 hour Rating r p m	Gear Ratio.	Total Weight lbs	Weight per horse-power lbs	Amperes One hour Rating	Continuous Rating At 750 volts	At 1,125 volts	At 1,500 volts
A	315	675	3 86	8,040	25 55	177	110	120	130
B	400	740	3·31	8,330	20 83	220	130	135	135
C	260	903	3 263	7,070	27 2	145	118	125	130
D	360	745	3·22	7,700	21 4	200	145	150	155
E	225	755	3·75	7,950	35 4	130	84	90	93

(*Note.*—The weight given includes gears, pinions, gear-case and suspension bearings)

The watt-hours per ton mile energy consumption for the train over the various services was almost exactly the same for all motors.

Temperature Rise by Increase of Resistance. It is sometimes preferable to use the increase of resistance of a motor as a basis for the calculation of its temperature rise, instead of using a thermometer. The advantage of this method is that resistance is measured by taking the voltage drop across the motor for a certain current, both of which are electrical measurements and simple to make with ease and accuracy. The temperature rise thus calculated, however, represents an average value, and while it avoids the need for reading thermometers in places which are difficult of access, it does not reveal the hottest part as does the thermometer. The method of calculation is as follows:—

If R_0 = Resistance at 0° C.
,, R_c = Resistance of motor when cold, at t_c degrees C.
,, R_h = ,, ,, ,, ,, hot, at t_h ,,
Temperature Coefficient for Copper, $a = \cdot 00428$ per 1° C.
(or $a = \cdot 00238$ per 1° F.)

by definition $$R_h = R_0\,(1 + at_h)$$
and $$R_c = R_0\,(1 + at_c)$$

$$\therefore \quad \frac{R_h}{R_c} = \frac{1 + at_h}{1 + at_c}$$

$$\frac{R_h}{R_c} - 1 = \frac{1 + at_h}{1 + at_c} - 1$$

$$\frac{R_h - R_c}{R_c} = \frac{a(t_h - t_c)}{1 + at_c}$$

$$\therefore\ t_h - t_c = \frac{R_h - R_c}{R_c} \times \left(\frac{1}{a} + t_c\right)$$

Hence temperature rise in degrees Centigrade

$$= \frac{\text{resistance increase}}{\text{resistance cold}} \times (234 + t_c)$$

Or for the Fahrenheit scale,
Temperature rise in degrees Fahrenheit

$$= \frac{\text{resistance increase}}{\text{resistance cold}} \times (421 + t_c - 32)$$

$$= \frac{\text{resistance increase}}{\text{resistance cold}} \times (389 + t_c).$$

The same formula can be used to calculate the hot resistance of a motor when the cold resistance is known, as is required when calculating rheostatic notches For example, the L. & N.W.R. motor used in calculations in Chapter VI and elsewhere has a cold resistance, at 20° C., of ·0615 ohms. To find its resistance at 80° C, the formula may be applied thus :—

$$60 = \frac{\text{resistance increase}}{\cdot 0615} \times (234 + 20)$$

Resistance increase = ·0145 ohms.
∴ Resistance at 80° C. = ·0615 + ·0145 = ·076 ohms.

A practical hint, well known on commercial test-beds, for fixing a thermometer in a difficult position is to place it exactly where required and then apply soft clay or " Plasticine " round the thermometer bulb. In this way a thermometer can be safely fixed to a radial surface such as a commutator or a field coil and in a position to be read easily.

CHAPTER XIII

REGENERATION: COMPARISON OF ELECTRIC TRACTION SYSTEMS

REGENERATION

The fact that a large proportion of the energy supplied to the motors of a train has ultimately to be absorbed in brake friction has from the beginning fired the imagination of electric traction engineers and turned their inventive faculties towards devising a means whereby this wasted energy can be "regenerated," i e the kinetic energy stored up in the train used to drive the motors and so return power to the line. Regeneration is inherent and automatic in the case of a cable tramway.

Now the problem of regeneration can be sharply divided into two parts, (*a*) that of regenerating the energy expended on acceleration, i.e. regeneration for ordinary suburban working, and (*b*) that of regenerating the energy expended on lifting the train up very long and steep gradients.

It may be said at once that regeneration has been achieved with very great success for the latter, while for ordinary train services it has proved an entire failure, with the exception of the mechanical regeneration adopted by some Tube railways.

Mechanical Regeneration. The simplest form of regeneration is the purely mechanical one of building stations on a hill. The effect of this is that much of the kinetic energy of the train is expended in lifting it and is available for acceleration on the down gradient when leaving the station. This principle, often known as "profiling" or "grading" the track, is in use on the Great Northern, Piccadilly and Brompton tube in London, and the Central London Railway The Piccadilly Railway employs an up grade of 1 in 66, and a down grade of 1 in 33; while the Central London employs an up grade of 1 in 60 (1·66 per cent.) for a distance of 500–600 feet, and a down grade of 1 in 30 (3·33 per cent.) for a distance of 240–300 feet. The down grade is

thus seen to be twice as steep and half as long as the up grade. The reason for the difference is that it would be bad practice for a train to pull up for a signal at danger on a 1 in 30 gradient, while a train would not leave a station till the signal was clear for the down-hill section The effect of this "profiling" is to place the station on a hill 8–10 feet above the normal line level. The cost of construction is probably not much increased, and the system minimises the production of objectionable brake dust. It is admirable for power economy by regeneration, but it renders the line unsuitable for non-stop or through running trains. Most of later "tubes" have not adopted it, e.g the Bakerloo ; and the factor of cost and inconvenience for through running would certainly be increased in the case of surface railways. On the Central London Railway, the regenerated energy resulting from this system of "profiling" amounts to 14 watt-hours per ton mile, or about one-third of the energy consumption of a train running at a schedule speed of 14 miles per hour. In Fig 129 a curve has been worked out representing the height in feet to which a train at various speeds must be lifted to absorb the whole of its kinetic energy.

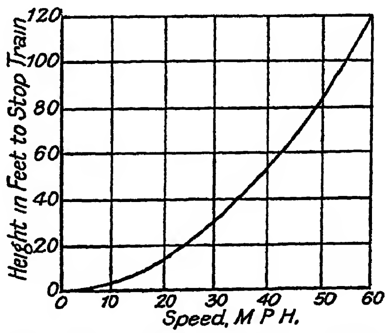


Fig 129.—Height of Station to stop Train at Various Speeds

$$\text{Height} \times \text{weight lifted} = \tfrac{1}{2}\,(\text{mass} \times \text{square of velocity}).$$

The curve shows at once the great height to which platforms would have to be raised to regenerate to any extent in the case of trains running at high schedule speed, and hence exhibits the limitations of this method.

Electrical Regeneration on Mountain Railways. As was pointed out at the beginning of Chapter IX a steam train descending a long and steep gradient is faced with two braking difficulties. Firstly, it is not possible to apply a sufficient brake power and keep it there because the leakage of air from the brake cylinders will cause the brake power to be gradually reduced, and secondly, even if a steady uniform brake power could be obtained the heat developed might reach dangerous proportions, sufficient to loosen the shrunk-on tyres and in severe cases even

to cause a wheel centre to loosen from its axle; furthermore the wear on an almost red-hot brake shoe would be very rapid. As a result the descent is made in a series of short runs; the train is allowed to reach a speed of about 25 miles per hour, brakes are applied and held on until the speed is about 5 miles per hour and are then released, the train again accelerates to 25 miles per hour, by which time the auxiliary reservoirs of the brakes have had time to become re-charged to full air pressure and the shoes and tyres to cool. Full brake power is now again available for the train, and this cycle of operations is continued throughout the descent. If the train is allowed to exceed a certain speed the brakes will be unable to retard it. The responsibility which is placed on the skill of the driver is evidently a heavy one, and a great number of accidents have been caused by failures of the human mechanism.

The speed of a heavy train on a down gradient is often limited by the permissible heating of the brake shoes, but with regeneration the speed can be increased to the safe speed for the track, taking curves, etc, into consideration, since the power brake is left out of action and there is consequently no heating of the brake shoes whatever. The motors, acting as generators, steadily return power to the line and this loading of the motors constitutes an electrical brake which is safe and self-regulating

A regeneration system which reduces the need for reliance on the driver and at the same time offers a considerable saving in the wear of brake shoes and tyres is naturally a great attraction to the electric railway engineer, and it cannot be too clearly understood that it is this phase of regeneration which is of primary importance. The saving of energy, which may reach 10–15 per cent. over mountain gradients, though valuable, is a secondary consideration; the return of energy to the line at a time when there may happen to be no train or other load to utilise it constitutes an embarrassment, and an artificial load, generally a water-rheostat, has usually to be provided at the generating stations to meet this emergency.

We may now consider briefly how regeneration has been accomplished on the several systems.

Regeneration on D.C. Systems. It is unfortunate that the shunt motor is so unsuitable for D.C. traction, since a system which used shunt motors would have a natural regeneration, a rise of speed causing the motor to generate. As the speed falls it would be easy to cut resistance out of the field circuit and thus maintain the voltage and so regenerate almost down to rest.

The series motor has no such inherent regulation and many attempts have been made to turn it into a shunt motor when regenerating by fitting separate shunt windings. Unfortunately the extra space inside the motor required for these coils, the consequent complication of the switch-gear, additional weight and cost have usually outweighed the resulting economy in energy Furthermore, since the motors are called upon to carry current for a longer period, their heating is increased and their rating reduced, or in other words a larger, heavier and more costly motor is required than would be the case without regeneration. Consequently, for suburban services of the usual kind, regeneration has not proved commercially possible.

On mountain services it has been done successfully, notably on locomotives of the Chicago, Milwaukee & St. Paul Railroad, where very heavy trains are hauled over very long and steep grades. The method adopted is that of separately exciting the motor fields by means of a small generator driven from one of the axles. The fields can be separately excited from storage batteries or from a motor-generator set driven from the line This is a very large and important electrification, and regeneration adopted is a great success, the trains descending the grades at a steady, uniform speed. The air brake is of course always available as a reserve.

It must be remembered that mercury rectifiers are not reversible in the same way as are motor-generators, rotary converters and transformers, and since power returned to the line may have to pass through the sub-stations it follows that regeneration is limited where rectifier sub-stations are used But where other trains in the same area are taking more load than the downhill train is regenerating, the regeneration only reduces the load without reversing it. The non-reversibility of the rectifier is therefore not an insuperable difficulty—the Midi Railway is a case in point.

Regeneration on Single-Phase Systems. The single-phase series motor is almost exactly analogous to the D.C. series motor in that it can be made suitable for regeneration by separate excitation of its fields. This can be done as before by means of a separate motor-generator or axle-driven generator, but an arrangement used by the Westinghouse Co. is one in which one motor of the four on a locomotive is used as a generator for furnishing current to excite the fields of the other three, these three only delivering power to the line. As the speed falls, the connection between the motors and the low tension side of the

transformer is altered, i e. the tapping point is shifted to suit the lower voltage The long hilly divisions of the Midi Railway, South France, use regeneration successfully on their single-phase locomotives.

Regeneration on Three-Phase Systems. The inherent regenerative characteristics of the three-phase induction motor have been fully described in the chapter dealing with three-phase railways, and the beginning of Chapter IX should be re-read in this connection

It is noticeable that the induction motor alone of A C machines has a natural and inherent regenerative power, all other motors requiring some separate excitation or other external apparatus which depends upon the driver for correct application.

The regenerative features of the induction motor are not impaired by the phase-converter used in split-phase working, so that split-phase locomotives are in the same category as three-phase so far as regeneration is concerned.

In conclusion, it is to be noticed that regeneration is only practicable on locomotives and not on multiple-unit trains Furthermore while "track profiling" enables the service to be effected with motors rated lower than would otherwise be necessary, any kind of electrical regeneration causes additional motor heating and reduces the time available for cooling, both of which necessitate a larger motor than would be required without regeneration.

Regenerative Electric Braking. Apart from the electro-magnetic braking which is sometimes used on tramway systems in which the motors can be made to generate current which excites electro-magnets, thus applying a brake to the track rails or the wheels or both, there is a simple method by which electric trains can in emergency use their own motors as generators, and so produce a braking effect

Referring to Fig. 130 and diagram of the motor power circuit, Fig. 34, the procedure is as follows :—

(1) Throw reversers to "reverse" position

(2) Trip the circuit breakers.

(3) Bring controller handle to first parallel notch.

Each pair of motors on the train, with their rheostats, now form a closed circuit, entirely cut off from the line supply. The motors are now evidently in parallel with each other generating only the feeble E M F. due to residual field. Now in a series motor which is suddenly allowed to generate without changing the direction of rotation, the back E.M F. tends to send a current

round the circuit which opposes the residual field. In this case, however, by throwing the reversers we have reversed the field connection, and hence the machines are free to excite themselves, but their polarity as generators will have been reversed If the respective E.M F.'s generated were exactly equal, no current would flow and no braking action would result. Actually, however, this is unlikely to occur, owing to slight differences of wheel diameter, air-gap and other magnetic properties, and one generates an E M.F. slightly higher than the other. A small current therefore flows round the circuit. In the case of the motor (A) generating the higher E M.F the current tends to strengthen its field flux and thus further increases the E M F.

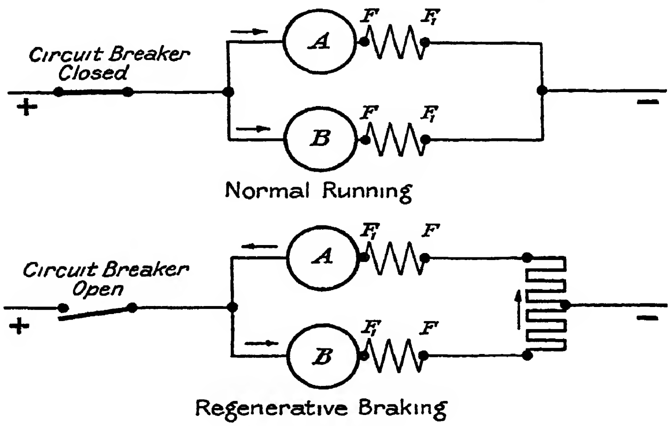


Fig. 130

generated. In the case of the motor (B) with lower E.M F. the current opposes its back E M.F , destroys and then reverses its field flux. In consequence, the pressure difference is now much greater, a considerable current flows, and in a short space of time A builds up as a generator, and pumps current through B. The direction of the current through the armature of B is the same as when it was fed with power from the line, but its field connections have been reversed, and it therefore tries to rotate in the opposite direction. The net effect is that the braking action is produced on the wheels of A motor owing to its acting as a loaded generator, while motor B tends not only to brake but even to reverse its wheels, the whole representing a powerful braking effect.

As soon as this effect is felt, the driver can move his controller round notch by notch to increase the braking effect by cutting out rheostat steps. The braking effect is, of course, proportional to the speed and reduces itself automatically as the speed falls, nevertheless as the braking operates on motor wheels only, and has no effect on trailer wheels it is advisable to apply sand to the wheels to prevent skidding, since the moment this occurs all electric braking effect ceases. This system is used in emergency only, in case of a failure of the normal air brake, but most railway companies keep their drivers trained to use it against such emergency

Comparison of Systems

Neglecting such combinations as the petrol-electric and turbo-electric locomotives, in which electrical apparatus is merely a form of gearing and clutch, the systems available for purely electric traction are: (1) High and low tension D C , (2) single-phase, (3) three-phase, (4) split-phase.

In making a fair comparison between these systems, it is not sufficient to consider the motors only, the distribution and generation must all be considered and the comparison made on the complete system from generator to track rails

Generation and Transmission. The prime mover will be little affected by the system chosen; it is uneconomical to generate and transmit bulk power from D C. generators and the main generators are nearly always three-phase units, with a voltage of about 11,000 volts For D C working this pressure will be used for distribution, transformed down and converted into D C. at sub-stations along the route

For single-phase working, single-phase generators are most commonly used but are relatively expensive since the generator is actually a three-phase machine with the winding left out of one of every three slots.

Three-phase generators for single-phase systems may be used (1) by earthing the neutral point to the track and connecting the terminals of the three phases to various sections of the trolley wire, or (2) by a motor generator at sub-stations For three-phase working the power can be generated at the desired voltage or at a high voltage for economical transmission and stepped down at transformer sub-stations.

The single-phase system is the most economical in transmitting unit power with a minimum cost of copper cables.

Rheostatic Losses. During starting, both the D.C. and

the three-phase systems involve large rheostatic losses, while the single-phase system has a high starting efficiency through avoiding rheostatic losses

Motor Efficiency. The D C. motor is very thoroughly developed, extremely reliable, and has the best possible operating characteristics for electric traction Its weight is lower than for the single-phase motor The three-phase motor is highly efficient and has the outstanding advantage of having no commutator Its operating characteristics are unsatisfactory for general service especially on account of the few speeds available, and the small air-gap is a very real objection from the standpoint of bearing maintenance

Weight. The single-phase motor is the heaviest and the train weight is further increased by the need for carrying a transformer

The chief advantages and disadvantages may be summarised thus ·—

D.C. System.

Advantages —Standard, well-tried motors, of low weight and cost, high efficiency, very good operating characteristics, any voltage up to 1,500 volts for multiple-unit trains and 3,000 volts for locomotives may be used A normal frequency of 50 cycles may be used for the generating plant.

Disadvantages —High transmission, distribution and contact line losses and frequent sub-stations, all on account of low contact line voltage. Overall cost of system therefore very high, and owing to the number of sub-stations, the type of machinery used in them, and the rheostatic losses on the trains, the overall efficiency from power-house to rail is the lowest. A drop in line voltage due to accidental concentration of traffic in one district will reduce the possible schedule speed.

Single-Phase System.

Advantages.—High trolley voltage, hence minimum distribution and trolley line losses Few track sub-stations. No rheostatic losses. Speed may be kept up by transformer tappings even if trolley voltage is low. Each sub-station and sometimes the power station supplies power over a wide area of track, producing a much higher load factor for transmission and lower peak load than is possible with the D C. system with separated sections. For example, each D C. sub-station may carry at a time two 1,000 horse-power trains on a 10-mile section, compared

with perhaps twenty 1,000 horse-power trains over a 50-mile section with single phase This is a very important advantage of the single-phase system. The saving of sub-stations more than offsets the higher cost of motors. Generating plant capacity is the lowest.

Disadvantages—Sub-station carried on every train Lower starting torque.

Motors in every way less satisfactory than for D C. in design, operating characteristics, commutation, cost, heating and maintenance Lower possible horse-power per axle on account of size of motor. Low power factor causes high relative cost and low efficiency of generating machinery The interference with telegraph and telephone wires along the track by electrical induction is a very serious matter with single-phase systems

Generating plant must be built for the same frequency as the motors, i e. 15 to 25 cycles, and is therefore somewhat more expensive than 50-cycle plant.

Three-Phase System.

Advantages.—Rugged and reliable motors of high efficiency No commutators. Perfect inherent regenerative power. Low weight.

Disadvantages—Small air gap, constant speed, high peak load on power station, rheostatic losses and low efficiency at starting, risk of overloading motors through difference of wheel diameter, low line voltage, hence need for sub-stations. Two trolley wires are required. Low power factor for cascade running.

Split-Phase System.

Advantages—All the advantages of single-phase distribution with high efficiency and other features of three-phase motors. Regenerative control equal to three-phase.

Disadvantages.—All the disadvantages of the three-phase motor. Extra cost, weight and losses of phase converter

As explained in Chapter IX, the three-phase and split-phase systems are suitable for special working only and are entirely unsuitable for general main-line or suburban working, which narrows the field for the majority of cases to a choice between D.C. and single phase.

The following table illustrates a comparison between D C. and single-phase current supply, and is taken from an article by Mr. L. Thormann.*

*"Choice of a System for Electric Traction on Main-Line Railways," *Engineering*, Vol. CXIV (1922)

Average Efficiency of Electric Traction Supply from Generator-Shaft to Wheel-Rim of Locomotive

	Direct Current at 3,000 volts, produced from Three-Phase	Single-Phase at 15,000 Volts produced	
		Direct	From Three-Phase
Locomotive	0·80	0·76	0·76
Overhead conductor .	0·90	0·92	0·92
Rotary converter . .	0·91	—	—
Motor-generator . .	—	—	0·80
Double transformation	0·90	0·91	0·91
Transmission	0·94	0·94	0·94
	0·555	0·60	0·48

With a motor-generator set (efficiency 0·86) instead of a rotary converter, the average efficiency of the D.C. supply would be 0·525, and with a mercury-arc power rectifier (efficiency 0·98) the average efficiency would be 0·595.

There is little doubt that the general characteristics of the single-phase system render it more suitable for locomotive operation than for multiple-unit trains, and the D.C. system is more suitable for a frequent and continuous traffic. Local conditions must be considered, however, and the impossibility of providing and operating sub-stations on the mountain routes of Switzerland and the infrequent service are factors which help to explain the preference for the single-phase system in that country.

When the Victorian Railways (Australia) electrified their suburban system around Melbourne (then the largest single suburban electrification in existence and now operating over 850 cars), complete tenders were called for both D.C. and single-phase systems for the purpose of ascertaining definitely the most economical system. The results, taken from *The Times Engineering Supplement*, November 20, 1912, are shown summarised in the following tables. The costs are now quite out of date for any but comparative purposes, but are relatively representative for a large suburban service.

Table 1 Capital Costs

Power Plant	*Direct Current Scheme.* £	*Single-Phase Scheme* £
Turbo-alternators, step-up transformers, auxiliary transformers and condensing plant	222,151	241,377
Power station switchgear, auxiliary motors, wiring and yard locomotives	46,956	46,667
High Tension Transmission:—		
20,000 V. underground cables	106,368	110,015
20,000 V. overhead lines	61,495	21,368
Sub-stations	378,605	41,905
Electrical Equipment of Permanent Way.—		
(*a*) Trolley wires (material only)		
For running roads	142,165	47,806
For sidings	4,264	4,264
(*b*) Erection of conductors, provision and erection of structures, insulators, connecting cables, section switchgear and track bonding	415,851	359,846
Alterations to Ways and Works:—		
(*a*) Increasing height under bridges	4,350	24,800
(*b*) Altering telegraph and telephone wires	20,000	181,632
Rolling Stock:—		
Electrical equipment of 500 motor coaches and 450 trailer coaches	947,232	1,977,344
	£2,349,437	£3,057,024

Table 2 Working Costs

Electrical Energy	*Direct Current Scheme* £	*Single-Phase Scheme.* £
Variable power house charges, including coal, water, stores and wages of coal and ash handling staff	59,700	58,400
Inspection and maintenance of high tension transmission lines	3,190	2,169
Operation and maintenance of sub-stations	12,456	1,940
Maintenance and renewal of track conductors	18,051	18,051
Maintenance of coach equipments:—		
(*a*) Inspection, cleaning, stores and small repairs	22,900	30,800
(*b*) Repairs and renewals	43,900	91,100
Interest charges on capital expenditure	93,977	122,281
	£254,174	£324,741

TABLE 3. SUMMARY OF CAPITAL COSTS.

Item	£	*Per cent.*
Boiler house equipment and structural steel work for generating station	427,720	18·8
Turbo-alternators and transformers . .	182,046	8·0
Condensing plant	85,251	3·8
Sub-station equipments	201,624	8·9
Switchgear, power station and sub-stations . .	140,070	6·2
High-tension feeder cables	259,121	11·4
Overhead track equipment	278,286	12·3
Bonds	20,000	·9
Train equipments	676,180	29·8
	£2,270,298	100·1

Table 1 shows that the train equipments are by far the largest item, the cost for the single-phase system being more than double that of the D.C. scheme and deciding the total in favour of the latter, in spite of the lower total cost of the other items for single-phase. The maintenance costs, Table 2, are also doubled for the single-phase scheme. In Table 3 the figures of the actual contracts placed are given and the items are shown as a percentage of the whole, for comparative purposes.

The British Ministry of Transport appointed an Advisory Committee which after careful study reported in favour of standardising on 1,500 volts D.C.; and the 1,500 or 3,000-volt electrifications on the Midi Railway (France), Holland, North Spain, South Africa, Brazil, Chili, Japan, India, Western Australia and New South Wales indicate beyond question the modern tendency to prefer the high voltage D.C. to the single-phase system. Germany, Austria, Switzerland and Sweden use the single-phase system chiefly or exclusively, and a voltage of 16,000 to 17,000 volts at 16$\frac{2}{3}$ cycles is becoming standard. Italy uses 3,000 volts 15 frequency three-phase current.

CHAPTER XIV

COMPLETE CALCULATIONS FOR AN ELECTRIC TRAIN

In this chapter, calculations in connection with an actual electric train equipment are set out. The data are the weights of each car and of the apparatus and passengers, the characteristic curves of the motor proposed and a profile and plan of the track and the time-table required The motor coach is to be equipped with only two motors, so that the whole weight of the coach is not available for adhesion.

The objects of the calculations are :—(1) to design the rheostat steps for the smoothest and best acceleration possible without risking the slipping of the driving wheels ; (2) from the rheostat curves to fix the best setting for the current limit relays and thus (3) to ascertain the highest possible safe acceleration rate ; (4) using the information so gained to construct average run curves for the service, including curves and grades, and (5) thence to decide the capacity or otherwise of the motor to operate the service ; (6) the amount of coasting possible and the amount of reserve available for making up time in emergency ; (7) to estimate the energy consumption in watt-hours per ton mile ; (8) to ascertain whether the driving wheels can ever speed up to the danger limit if allowed to slip and continue slipping.

While the last named matter is perhaps special to this particular example in that a two-motor equipment is employed, the remainder of the calculations have always to be made either by the contractors or railway engineers for any electrification scheme and are therefore set out fully.

Average Run. Fig. 131 shows a profile and plan of the track. The average run is to be based on a run from A to Q and back to A, up to the moment of starting again for the next trip. It allows for stopping for 20 seconds at all intermediate stations and for 3 minutes at Q and A. The distance from A to

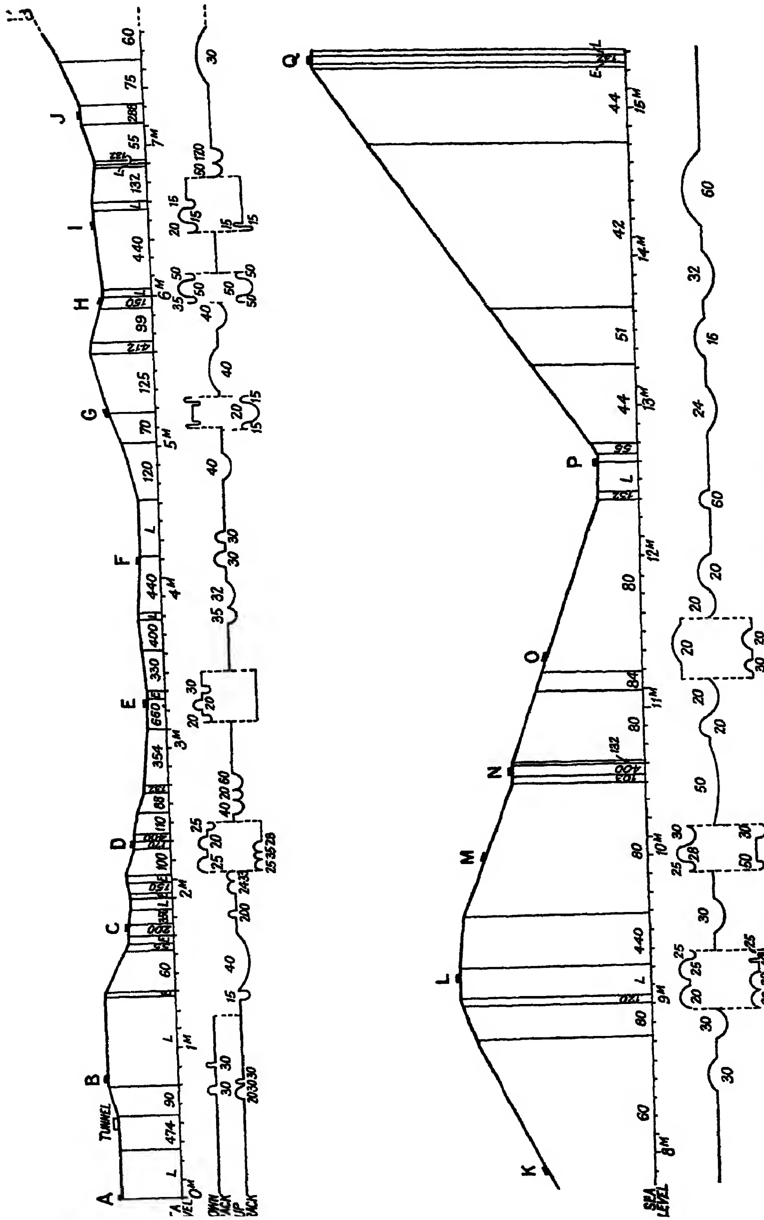


FIG. 131.—Profile and Plan of Track.

Q is 15·403 miles and the schedule time from A to Q is 39 minutes 22 seconds, and from Q to A is 38 minutes 41 seconds There are thus 32 separate runs on the round trip

The total times for the round trip are therefore .—

Down trip	= 39 mins	22 secs.	
Up trip	= 38 ,,	41 ,,	
3 minute stops at Q & A	= 6 ,,	0 ,,	
Total schedule time	= 84 mins.	3 secs.	
Total stops	= 16 mins.	0 secs.	(30 stops of 20 secs each and 2 of 3 mins.)
Total running time	= 68 mins	3 secs	

Average schedule time of run = 157·6 secs.
Average running time of run = 127·6 secs.
Average length of run = 0·9627 mile = 5,080 ft.

Grades. The figures marked along the Sea Level line in the diagrams indicate the gradients in the designation of 1 in N, the values of N being shown.

The method adopted is that stated in Chapter XII of assuming that half the kinetic energy of the down grades is lost and half regenerated. Since a round trip is being considered it is not here necessary to sum the individual grades, since it is known from the railway working time table that the height of A is 67 ft and of Q is 520 ft. above sea level. The difference, 453 ft, will be a total rise in one direction and a total fall in the other, and for the round trip the total rises and total falls will each be 453 ft Deducting half the falls from the total rises, the net grade is 226·5 ft, in a total distance of 30·806 miles.

The average equivalent grade is therefore

$$1 \text{ in } \frac{30{\cdot}806 \times 5{,}280}{226{\cdot}5}, \text{ i e. } 1 \text{ in } 718 \text{ (up).}$$

$\therefore$ Average train resistance due to grades is $\frac{2{,}240}{718} = 3{\cdot}12$ lbs. per ton.

Curves. The length of each curve scaled off the diagram and the total length of curve of each radius is shown in Column A of the following table. Column B shows the resistance of each curvature in lbs. per ton, curve resistance being taken as equivalent to a tangent grade of 1 in 0·5 R, where R is the radius of the curve in feet.

The fourth column is the value in Column A multiplied by that in B, and the sum of this fourth column divided by the

total distance of the round trip evidently gives the average resistance due to curves = 1·13 lbs per ton.

Curvature in Chains	Down Trip			Up Trip	
	A	B			
	Total Length Miles	Resistance Lbs per ton	A × B	A.	A × B
15	·10	4 52	452	18	814
16	·26	4 24	1 10	26	1 10
18	·10	3 77	377	—	—
20	1·55	3 39	5 25	1 34	4 54
24	·38	2 83	1 07	38	1 07
25	·27	2·72	734	1	272
28	·21	2 42	508	07	·169
30	1·44	2 26	3 25	1 5	3 39
32	·50	2·12	1 06	·5	1 06
33	·06	2 05	123	06	·123
35	·14	1 94	272	15	·291
40	1·13	1 7	1 92	1 15	1 95
50	·68	1·36	925	78	1 06
60	·70	1·13	·791	70	·791
80	·09	0 85	077	09	077
120	·09	0 56	050	·09	050
200	04	0 34	·014	·04	·014

Totals (down) 17 97 (up) 16·77

Total (up and down) 34·74

$$\text{Average curve resistance} = \frac{34{\cdot}74}{30{\cdot}81} = 1{\cdot}13 \text{ lbs. per ton.}$$

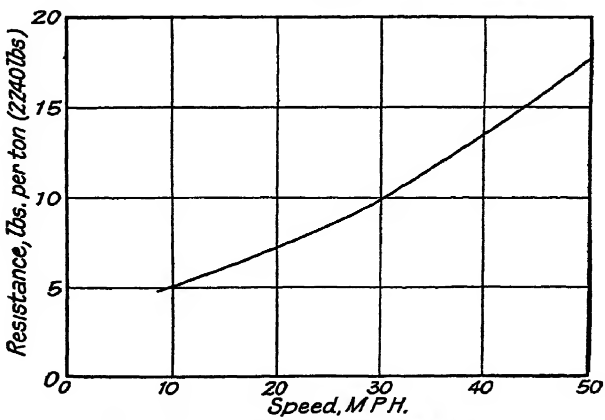


FIG. 132.—Resistance of 2-Car Train.

The average equivalent resistance due to grades and curves is therefore 4·25 lbs per ton.

The train resistance is taken from Fig. 132

Weights. The train to be considered is a 2-coach train, shown in outline in Fig 133. The two driving motors are on the rear bogie. The weights are as follows .—

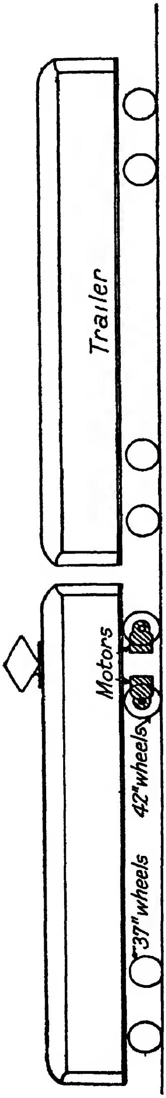


Fig 133.—Outline of 2-car Train.

Motor Coach.

Weight of body only	=	50,504 lbs.
,, ,, motor bogie without motors	=	18,256 ,,
,, ,, 2 motors complete	=	15,400 ,,
,, ,, trailer bogie	=	13,000 ,,
,, ,, control apparatus, cables, brakes, and all equipment	=	11,273 ,,
Total weight, empty	=	108,433 lbs.
	=	48·4 tons.
Full seating capacity = 79 passengers at 140 lbs each	=	11,060 lbs.
Total weight, loaded	=	119,493 lbs.
	=	53·3 tons.

Trailer Coach.

Total weight, empty	=	52,300 lbs.
	=	23·4 tons.
Full seating capacity = 57 passengers at 140 lbs each	=	7,980 lbs.
Total weight, loaded	=	60,280 lbs.
	=	26·9 tons.

Total weight of 2-coach train, empty	=	160,733 lbs.
	=	71·7 tons.
,, ,, ,, ,, fully loaded	=	179,773 lbs.
	=	80·1 tons.

Weight available for Adhesion.		*lbs.*
Weight of one motor bogie	=	18,256
,, ,, 2 motors, complete	=	15,400
,, ,, pantograph, placed exactly over motor bogie	=	1,080
,, ,, half of car body	=	25,252
,, ,, half of control apparatus, etc.	=	5,636
		65,624 = 29·3 tons.

This adhesive weight is required for fixing the setting of the current limit relay, which must be less than the current which will just slip the wheels under the worst conditions, i e. with the car empty. The weight on the driving wheels with the car empty fixes the adhesive weight for these calculations

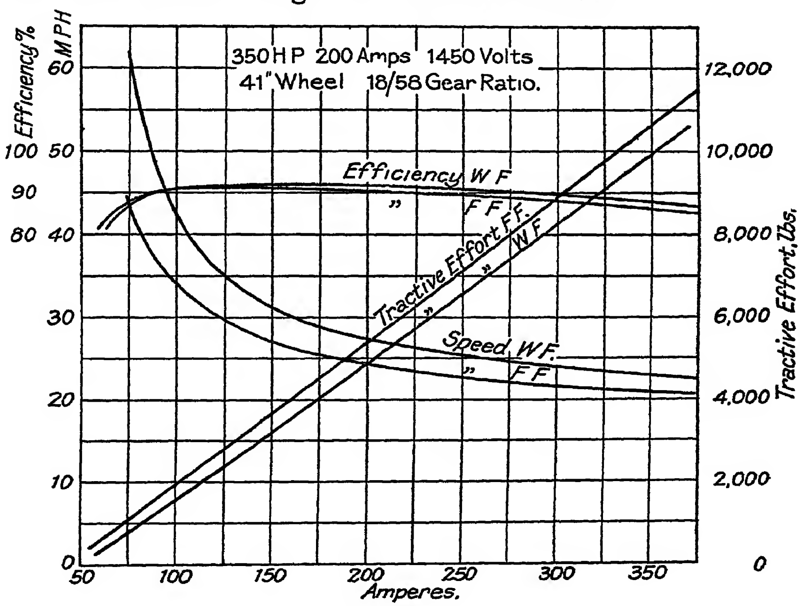


Fig. 134.

Maximum Tractive Effort. It was decided that the maximum safe value of the coefficient of adhesion, to suit local conditions, should be taken as 22·5 per cent.

The maximum tractive effort, beyond which the wheels will slip, is therefore

·225 × 65,624 = 14,750 lbs , or 7,375 lbs. per motor.

From the motor characteristic curve, Fig. 134, the current

corresponding to a tractive effort of 7,375 lbs per motor with full field is 258 amps. When these calculations were first made the car weights were estimated at somewhat lighter than the weights have proved and a limit of 7,100 lbs or 250 amperes was adopted for calculations, which setting will be retained to allow a margin of safety against wheel slip, the actual coefficient of adhesion used being therefore 21·6 per cent

It should also be pointed out that that part of the tractive effort which is used in accelerating the revolving masses (wheels, gears and armatures) does not require adhesion between wheel and rail but is independent of it, and the tractive effort could in consequence be slightly increased on this account The effect, however, is small for only 2 armatures and 4 wheels and it has been decided to retain the extra margin of safety instead of increasing the relay setting.

Calculation of Rheostat Steps. The arrangement of rheostats is similar to that shown in Fig 36 using 8 series and 4 parallel notches before passing into weak field.

The motor resistance is as follows :—

Armature	0·125	ohms	
Short field ·077, Remainder of field ·058	0·135	„	(full field)
Interpoles	0·042	„	

Total resistance per motor = 0·302 ohms at 20° C.

Rated temperate rise is 65° C., i.e. hot temperature is 85° C.

The resistance of motor at 85° C. is calculated from the formula deduced in Chapter XII thus :—

$$\text{temperature rise} = \frac{\text{resistance increase}}{\text{resistance cold}} \times (234 + \text{cold temperature})$$

$$\therefore \text{ resistance increase} = \frac{65 \times \cdot 302}{254} = \cdot 0773 \text{ ohms.}$$

$$\therefore \text{ resistance at } 85^\circ \text{ C.} = \cdot 38 \text{ ohms per motor.}$$

It is desired that the current on the first notch shall be low to avoid undue jerk at starting, when passengers are not expecting it, and to provide an easy notch for shunting purposes. The current value chosen is 216 amperes Then the total hot resistance of the circuit at starting must be

$$\frac{\text{line pressure}}{\text{current}} = \frac{1{,}450}{216} = 6{\cdot}72 \text{ ohms.}$$

Deduct Hot Resistance of 2 motors = 0·76

Total value of rheostats = 5·98 ohms or 2·99 ohms per motor

The full parallel full field and weak field speed-current curves are redrawn on Fig 135 and the full series curve and the first notching curve are calculated as explained in Chapter V and drawn in The current therefore will rise to 216 amperes on the first notch and fall away with increasing speed along curve 1.

The remaining series notches are found by the process of interpolating curves between No 1 and No. 8, the slope of each curve being gradually reduced. Resistance values found in this way were 2·386, 1·784, 1·322, ·859, ·547 and ·235 ohms. The calculations of the corresponding notching curves and of the first and full series curves are shown in table on next page

The rheostat values above are in ohms per motor, and the last value, ·235 ohms, represents half of resistance JR (Fig. 36) which is not used in parallel. JR therefore = ·47 ohms. The rheostat resistance per motor for the first parallel notch will therefore be $\frac{5{\cdot}98 - {\cdot}47}{2} = 2{\cdot}755$ ohms, and for the second and third notches, 1·549 and ·624 ohms The notching curves in parallel can then be calculated as shown in the table below.

Parallel Notching Curves

Amps per Motor	Rheostat Drop			Back E M F.			Actual Speed		
	Ohms 2 755	1 549	624						
	9	10	11	9	10	11.	9	10	11
150	413	232	94	980	1,161	1,300	19 0	22 5	25·2
200	550	310	124·5	824	1,064	1,250	14·5	18 8	22·1
250	688	387	156	667	968	1,199	11·2	16 2	20 1
300	825	464	187	511	872	1,149	8 25	14·1	18 6

The actual rheostat values are $R_1 = RR_1 = 1{\cdot}205$, $R_2 = RR_2 = {\cdot}925$, $R_3 = RR_3 = {\cdot}624$ and JR = ·47 ohms, all at 170° C. temperature rise, which is based upon 25 starts per hour

The notching curves are shown plotted in Fig. 135, from which

SERIES NOTCHING CURVES

Amps. per Motor.	Ir drop per motor (volts).	Rheostat Drop (Volts).								Back E.M.F. (Volts).									Actual Speed, m p h									
		Ohms 2 99	2 386	1 784	1 322	859	547	235	0																			
		Notch 1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	Full parallel	Full parallel from Curve	1	2	3	4	5	6	7	8
150	57	449	358	268	198	129	82	35	—	219	310	400	470	539	586	633	668	1,393	27	4 25	6 0	7 75	9 1	10 4	11 4	12 25	12 92
200	76	598	477	357	264	172	109	47	—	51	172	292	385	477	540	602	649	1,374	24 25	9	3 04	5 15	6 8	8 4	9 5	10 6	11 42
250	95	746	596	444	329	214	137	59	—	—	34	186	301	416	493	571	630	1,355	22 7	—	57	3 1	5 05	6 95	8 25	9 58	10 52
300	114	898	716	536	396	258	164	70	—	—	—	75	215	353	447	541	611	1,336	21 6	—	—	1 21	3 48	5 7	7 25	8 8	9 88

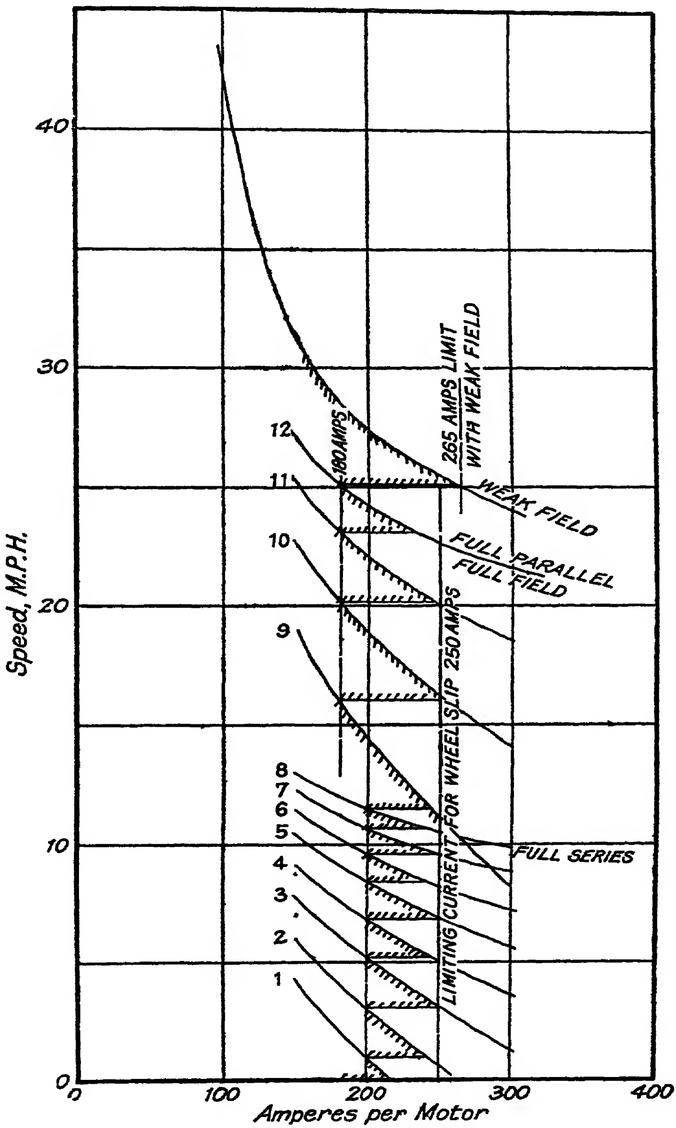


FIG. 135.—Notching Curves.

it will be seen that the limit relay setting requires to be 200 amperes to ensure that current does not rise at any time to a higher value than 250 amps. during the series period. It will be seen that the small number of parallel notches makes it impossible to maintain this setting in parallel as the current rush on each notch would greatly exceed 250 amps This involves (*a*) supplying a greater number of notches in parallel (which does not suit this control arrangement), or (*b*) reducing the relay setting (which will reduce the acceleration rate) or (*c*) providing a special coil on the limit relay to reduce the setting in parallel only. This last was the action taken, and the new coil shown in the power circuit of Fig 36 is energised from an interlock on one of the parallel line switches and is therefore energised in parallel only, and the acceleration will therefore be somewhat reduced in parallel.

Using a planimeter to average the current curve in Fig. 135 the average current in series is 220 amps , the speed rising to 11·5 m.p h , while during parallel the average current is 210 amps., the speed rising to 25·1 m p h. at the moment of reaching weak field

Effective Weight. When the total effective weight has been found, all the requisite data for calculating the speed-time curve will be to hand. The calculations are shown below.

Weight of armatures, each . . .	2,020 lbs.
Diameter of armature	20 ins.
Weight of gear wheels, each . . .	540 lbs.
Pitch circle diameter of gear wheel . .	29 ins
Gear ratio 58/18	3·22 to 1.
Weight of 42-in. driving wheels, each .	996 lbs
Weight of 37-in trailing wheels, each .	851 lbs.

2 *Armatures.* Radius of gyration of armature,

$$k = 0{\cdot}7 \times \text{armature radius} = 7 \text{ ins.}$$

Rotary inertia,

$$= 2 \times \mathrm{W} \times \frac{k^2\gamma^2}{r^2} = 2 \times 2{,}020 \times \frac{7^2 \times 3{\cdot}22^2}{21^2} = 4{,}650 \text{ lbs}$$

2 *Gear Wheels.* Radius of gyration

$$k = 0{\cdot}8 \times 14{\cdot}5 = 11{\cdot}6 \text{ ins.}$$

Rotary inertia,

$$= 2 \times \mathrm{W} \times \frac{k^2}{r^2} = 2 \times 540 \times \frac{11{\cdot}6^2}{21^2} = \quad 330 \text{ lbs}$$

4 *Driving Wheels.* Radius of gyration

$$k = 0{\cdot}77 \times \text{radius of wheel}$$

Rotary inertia,

$$= 4 \times \text{W} \times \frac{k^2}{r^2} = 4 \times 996 \times \cdot77^2 = \quad 2{,}360 \text{ lbs.}$$

12 *Trailing Wheels.*

$$\text{Rotary inertia} = 12 \times 851 \times \cdot77^2 = \quad 6{,}050 \text{ lbs}$$

$$\begin{aligned} \text{Total Rotary Inertia} &= 13{,}390 \text{ lbs.} \\ &= 5{\cdot}98 \text{ tons.} \end{aligned}$$

Rotary inertia expressed

$$\text{as percentage of weight of empty train } \frac{5\;98}{71{\cdot}7} = 8{\cdot}3 \text{ per cent;}$$

$$\text{as percentage of weight of loaded train } \frac{5\;98}{80{\cdot}1} = 7{\cdot}5 \text{ per cent.}$$

Speed-Time Curve.

Now F = 102 WA,

where W = net effective weight in tons = 1·075 × dead weight.
A = acceleration in m p h. per sec.
F = accelerating tractive effort in lbs.

If now all calculations are worked out at per ton of dead weight the formula becomes

$$\text{A} = \frac{f \text{ in lbs. per ton of dead weight}}{102 \times 1{\cdot}075}$$

$$= \frac{f}{109{\cdot}6}$$

This will enable train resistance to be kept in lbs. per ton and all figures small.

From the start to full series, the average current is 220 amps., which corresponds to a tractive effort of 6,040 lbs. per motor. Each motor deals with 40·05 tons of dead weight, and the tractive effort is therefore equivalent to $\frac{6{,}040}{40{\cdot}05} = 151$ lbs. per ton.

$$\left.\begin{array}{l} \left.\begin{array}{l}\text{Average curve resistance}\\ \quad = 1{\cdot}13 \text{ lbs. per ton}\\ \text{Average grade resistance}\\ \quad = 3{\cdot}12 \text{ lbs. per ton}\end{array}\right\} = \;4{\cdot}25 \\ \text{Mean train resistance} \\ \qquad 0 \text{ to } 11{\cdot}5 \text{ m p h} \;=\; 10{\cdot}0 \end{array}\right\} 14{\cdot}25 \text{ lbs per ton.}$$

Net Accelerating Tractive Effort = 136·75 lbs. per ton

$$\text{Acceleration} = \frac{136{\cdot}75}{109{\cdot}6} = 1{\cdot}25 \text{ m.p.h. per sec.}$$

$$\text{Time taken to reach full series} = \frac{11{\cdot}5}{1{\cdot}25} = 9{\cdot}2 \text{ secs}$$

Distance travelled to full series = 78 ft.

From full series to full parallel, the average current is 210 amps., which corresponds to a tractive effort of

5,700 lbs per motor = 142·5 lbs. per ton.

Average grade and curve resistance = 4·25 }
Mean train resistance, } 11 25 ,, ,, ,,
11·5 to 25·1 m p h. = 7·0 }

Net accelerating Tractive Effort = 131 25 lbs. per ton.

$$\text{Acceleration} = \frac{131{\cdot}25}{109{\cdot}6} = 1{\cdot}2 \text{ m.p h. per sec.}$$

Time to reach full parallel

$$= \frac{25{\cdot}1 - 11{\cdot}5}{1{\cdot}2} = 11{\cdot}3 \text{ secs.}$$

$$= 20{\cdot}5 \text{ secs from the start.}$$

Distance travelled during parallel = 303 ft. = 382 ft. from the start.

The current now increases to 255 amps. with weak field and the motors are running on the speed curve. The calculations for the rest of the curve are given below.

Braking rate will be taken at 2 m.p.h. per sec and the braking line can be drawn in, ending at 127·6 secs. as required.

Coasting. Having plotted the speed-time and current-time curves from the above tables, as shown in Fig. 136, it seems that coasting will take place at an average speed of about 35 m.p h. The mean resistance for coasting is taken at a speed of 15 per cent. above this mean, i e. at 40 m p.h. as explained in Chapter XI, page 240. The mean resistance is therefore 13·5 lbs. per ton

The gear friction taken from Fig. 123 at 35 m.p h. will be of the order of 75 lbs. per motor, i e. 1·85 lbs per ton, and the total resistance during coasting will therefore be 13·5 + 4·25 + 1·85 = 19·6 lbs. per ton. The deceleration rate is therefore $\frac{19\ 6}{109{\cdot}6}$ = ·18 m.p h. per sec. and the coasting line can now be drawn in.

The scale to which Fig. 136 is drawn is 1 inch = 10 m p h. and 1 mile = 20 secs., hence 1 sq. inch = 293·3 feet. The required area of the run curve is therefore $\frac{5{,}080}{293{\cdot}3} = 17{\cdot}35$ sq. ins. The coasting line is drawn in as shown, the position being determined by trial and error, using a planimeter for measuring the area. The distance curve is also drawn in and the current per motor plotted

It will be seen that cut-off takes place at 45 seconds and

Speed.	Amps per Motor	Tractive Effort		Train Resistance	Net Accelerating Tractive Effort		Speed Increment.	Mean Acceleration	Time Increment	Time from Start.	Mean Speed	Distance Increment.	Total Distance
m p h		lbs per Motor.	lbs per Ton.	lbs. per ton.	lbs. per ton	Mean	m p h	m p h per sec.	secs	secs.	m p h.	ft.	ft.
25·1	255	6,720	168	8 5	155					20·5			382
						126·25	2·9	1·155	2·5		26·55	97	
28	187·5	4,430	111	9·3	97·45					23			479
						86·6	2	·79	2·53		29	107 5	
30	162	3,600	89·9	9·9	75·75					25 5			587
						64·45	3	·587	5·12		31 5	236	
33	136·5	2,720	67·9	10 5	53 15					30·6			823
						47·95	2	·438	4 57		34	227·5	
35	125	2,350	58·7	11·7	42·75					35 2			1,051
						40 35	2	·368	5·44		36	286 5	
37	117	2,190	54·7	12·5	37·95					40 7			1,338
						33·40	2	·305	6 56		38	365	
39	110	1,850	46 2	13·1	28 85					47·3			1,703
						27·40	1	·25	4 0		39·5	231	
40	107	1,750	43·7	13·5	25·95					51 3			1,934
						24 05	1	·219	4·57		40 5	271	
41	104	1,620	40·4	14	22·15					55·9			2,205
						21·15	1	·193	5·19		41 5	315	
42	101	1,550	38·7	14·3	20·15					61·1			2,520
						19·20	1	·175	5·72		42 5	357	
43	99	1,490	37·2	14·7	18·25					66 8			2,877
						16	2	·146	6·85		44	403	
45	94	1,340	33·5	15·5	13·75					73·7			3,280

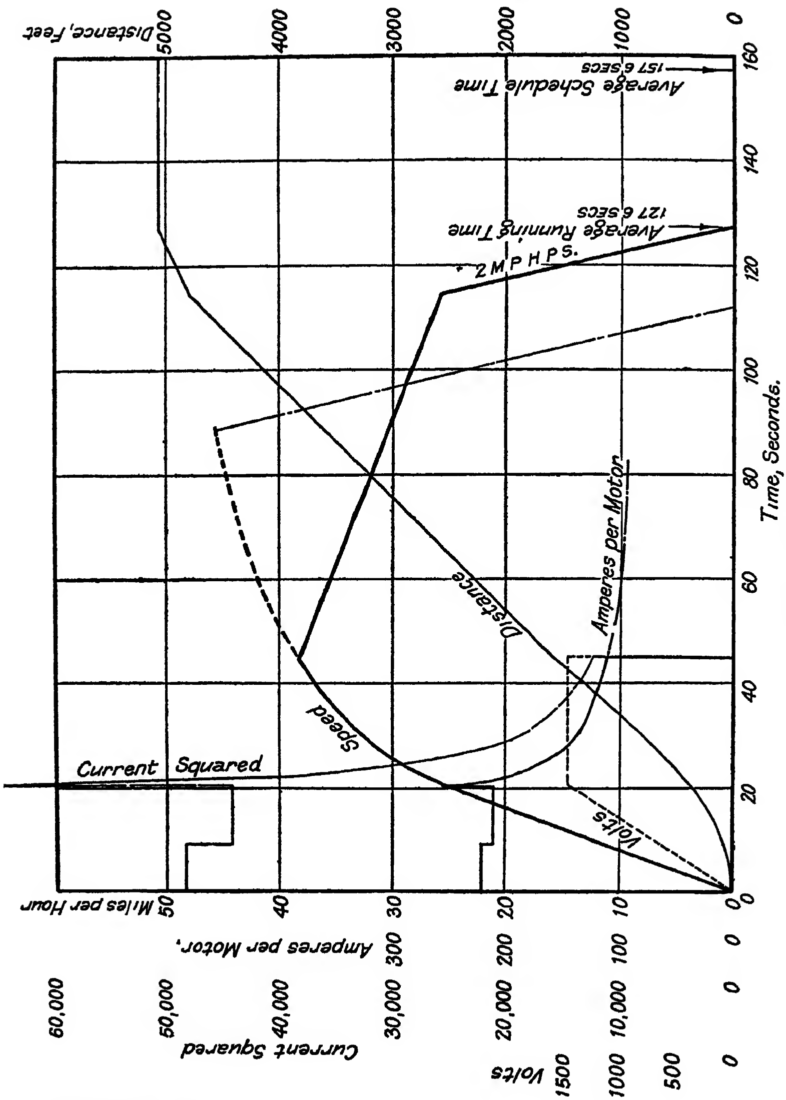


FIG. 136.—Run Curve

braking begins at 114·5 seconds The coasting time is therefore 69·5 seconds or 54·6 per cent , which high percentage will evidently help towards producing a low energy consumption. The chain-dotted curve shows the minimum time the run can be made in,

i e. 112 secs., which allows a leeway of 15·6 seconds or 21·2 per cent. of the running time.

Energy Consumption. The current scale chosen is 1 inch = 100 amperes, and the area of the current-time curve is therefore 2,000 ampere-seconds per square inch.

At 1,450 line volts, 1 sq inch = 2,900 kilowatt-seconds = ·806 K W H.

The area of this curve measures 3·93 sq. inches, which is therefore equivalent to 3·165 K W.H., and the watt-hours per ton mile $= \frac{3 \cdot 165}{40 \cdot 05 \times \cdot 9627} = 82 \cdot 2$.

Horse-Power of Motors. The maximum power is developed at the end of rheostatic starting, i.e. when the current is 255 amps, the tractive effort being 6,720 lbs per motor and the speed 25·1 m p h. The momentary horse-power is then $\frac{6{,}720 \times 25 \cdot 1 \times 88}{550 \times 60} = 450$ h.p, or 25 per cent above the nominal rating, which is quite satisfactory.

Heating of Motors. The diagram shows the "current squared" curve, obtained by plotting the square of each current value The area of this curve is found to be 7·2 sq. inches, i e. $7 \cdot 2 \times 20{,}000$ amp^2 secs. The time over which current is to be averaged must include the stops and will therefore be 157·6 seconds. The mean value of current squared averaged over the whole schedule time is therefore $\frac{7 \cdot 2 \times 20{,}000}{157 \cdot 6} = 9{,}150$, and the root-mean-square current is $\sqrt{9{,}150} = 95 \cdot 6$ amps.

The voltage rises from zero before starting to 1,450 at full parallel and then continues constant until cut-off, when it falls to zero again. The area of the voltage curve is therefore 50,350 volt-seconds, which over the whole schedule time gives an average equivalent voltage of 320 volts.

No thermal characteristic curves of this motor are yet available, but the continuous rating current at 750 volts is 145 amperes, so that it is evident that the motor, on this average run, will not even approach the standard temperature rise and is therefore quite satisfactory from the point of view of heating.

Acceleration on Level Track. If the starting current up to full parallel be averaged at 215 amperes, representing a tractive effort of 5,870 lbs per motor or 146·6 lbs. per ton, and the mean train resistance taken at 6 lbs. per ton, there being no deductions

for curve and grade, the net accelerating tractive effort will be 140·6 lbs per ton and the mean acceleration 1·28 m p h. per sec.

Balancing Speed on Level Track. The train will reach its "balancing" speed, i.e. steady maximum speed on level tangent track when the train resistance exactly balances the tractive effort and leaves no margin to produce acceleration.

The resistance curve has been produced to obtain the estimated value at 60 m.p.h. in the following table

Speed, m p h.	40	45	50	60
T E., lbs. per motor . . .	1,750	1,340	1,100	780
T.E., lbs. per ton	43·7	33·5	27 5	19·5
Train resistance, lbs. per ton .	13 5	15·5	17 74	23

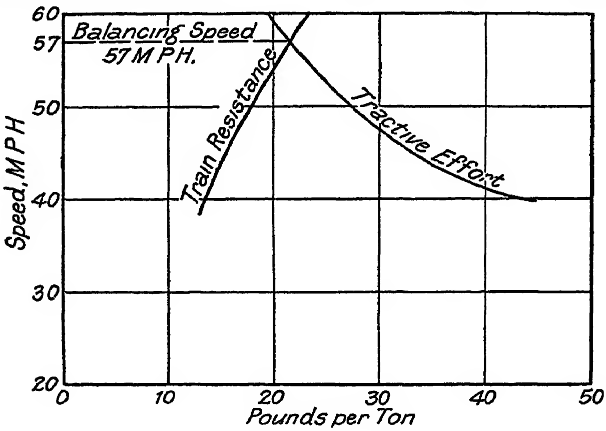


FIG. 137.

The tractive effort and train resistance, both in lbs. per ton, are shown plotted against speed in Fig. 137, the intersection at 57 m.p h. being evidently the balancing speed.

Slipping of Wheels. There was some fear, with the limited adhesion on these motor coaches, that if the wheels on a rear car began to slip they would continue to do so and might reach a dangerous speed, since the current limit relay affords no protection. The matter was investigated by plotting the tractive effort of the motors and the friction of a skidding wheel to the same time base in order to determine the speed at which these two opposing quantities would balance.

Galton * gives test figures for the coefficient of friction between

* "On the Effect of Brakes upon Railway Trains." Inst. of Mech. Eng., 1879.

wheel and rail for a skidding wheel, i e. for relative motion between wheel and rail, which are included in the table below.

Speed in miles per hour	27·3	34·1	40 9	47·7	54 5	60
Coefficient of sliding friction (μ)	·070	·065	·057	·04	·038	027
$\mu \times$ adhesive weight per motor (lbs.)	2,295	2,130	1,870	1,312	1,248	886
Weak Field tractive effort, from curve (lbs.)	4,840	2,520	1,640	1,200	920	760

The curves of skidding friction and tractive effort are shown plotted in Fig. 138

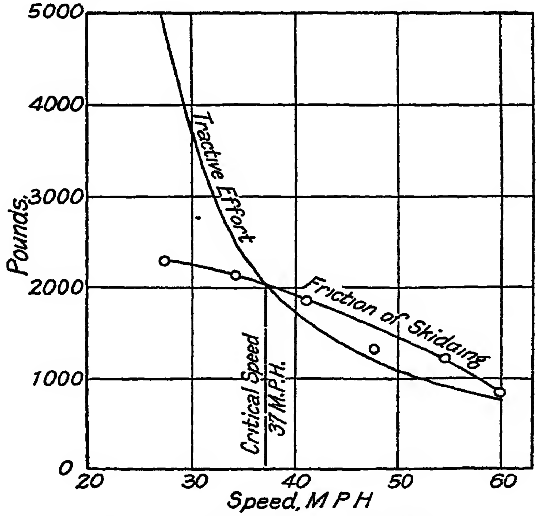


FIG. 138.—Slipping of Wheels.

Galton states that the fall of μ with increasing time, so noticeable between wheel and cast-iron brake shoes, is not very marked for a skidding wheel—as might reasonably be expected It will be noticed that the value given for μ at 47·7 m.p.h. is not on a smooth curve with the rest, but whether a mean line is drawn or this value ignored the curves will intersect at 37 m p.h. The gaps at the rail joints will impose a considerable drag on a slipping wheel and it is safe to say that a dangerous speed will not be obtained. This conclusion might not apply in climates where snow and sleet on the rail are encountered, or if oil or wet dead leaves are found on the rail.

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